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GEOTHERMAL ENERGY IN T

2

THE PACIFIC REGION

by

L. T. Grose and G. V. Keller
Colorado School of Mines

May, 1975

Office of Naval Research Contract
No. N00014-71-A-0430-0004

3

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ABSTRACT

The United States Navy has special energy requirements that make t use of geothermal energy especially attractive at certain bases. Usual fuel oil transported moderate to great distances by ship serves to meet these requirements. If geothermal energy at remote bases is available for space heating, electricity generation, and - in the future - for synthesis of high-energy fuel (hydrogen), the bases would be largely energy independent and would be alleviated of costly dependence on supply ships especially critical in times of international crises.

This report is a first phase study of the Intra- and Circum-Pacifi region for delineation of areas that appear to warrant exploration for geothermal energy sources which may be utilized by the United States Na Basic tectonic, volcanic, heat flow, and thermal spring data are plotte on regional Pacific quadrant maps at scale of 1:20,000,000. Areas most attractive for further geothermal investigations are manifest by tensio neotectonism, Pliocene-Quaternary volcanism, supernormal heat flow, and occurrence of high-temperature springs. Thermogeologic regime of basically similar simatic Pacific areas is reviewed for the Galapagos Island Hawaiian Islands, and Samoan Islands, and numerous small volcanic islan are selectively pointed out to have possibilities for geothermal develo ment. In the island-arc environment Adak, Fiji Plateau, Guam, and the Philippines are briefly described. A note on possible occurrence of ge pressured sections in the Circum-Pacific is included. The results of detailed geophysical studies on geothermal prospects at Lualualei, Oahu Hawaii and Adak, Alaska are presented.

The role of geology, geophysics, and geochemistry in geothermal energy exploration is briefly described. Geothermal energy is being con verted to electricity at the present time at eight sites, briefly descr in the Pacific region: The Geysers, California; Cerro Prieto, Mexico; Ahuachapan, El Salvador; Wairakei and Kawerau, New Zealand; Otake and Matsukawa, Japan; and Pauzhetsk, Kamchatka. Costs for geothermal explo tion, development, and electricity generation are outlined.

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I. INTRODUCTION

It is clear that energy resources are not now as easily available to the citizens of the United States as they were a few years ago, as recently as 1972. The reasons for the development of an "energy crisis" are complex and can be debated at length, but the important fact that must be recognized is that energy fuels are not available in predictable amounts or at predictable prices, except in the very short term.

The fuels which we are short of are those which are most convenient; the easily transportable, high energy density liquid and gaseous hydrocarbons. For most of this century, more oil and gas were produced in the United States than in any other country, with peak production of oil of about 11.3 million barrels/day being reached in the year 1970. Since that time, domestic production has remained almost constant, declining by a few percent by 1975. While our production of petroleum from domestic sources has reached a plateau, our consumption of petroleum continued to increase, until in 1973, consumption reached 17.3 million barrels per day.

few percent by 1975. While our production of petroleum from domestic sources has reached a plateau, our consumption of petroleum continued to increase, until in 1973, consumption reached 17.3 million barrels per day. As a consequence, we are now importing 35 to 40 percent of our oil from foreign sources.

Having to import oil from foreign sources does not necessarily comprise an energy shortage, because vast amounts of oil are present in foreign oil fields, primarily in Africa, the Middle East and possibly, Asia. Presently known reserves in the United States are adequate to meet our present demand for only 6 to 7 years, while known reserves in foreign fields can supply world requirements for 20 to 30 years. Moreover, it is likely that a lower fraction of oil fields has been discovered outside the United States than within the country, and that major additional reserves will continue to be discovered even to the end of this century. Therefore, the worldwide supply of petroleum should be adequate to meet world needs for the rest of this century.

Our problem, then, is not so much one of shortage as one of political and economic disadvantage in having a significant part of our energy supplied from abroad. Economically, the cost is high, and in order to maintain a reasonably equal balance of payments, great care must be taken in limiting other imports, and efforts must be expended in developing exports. Of even greater concern than the economic aspect, though, is the fact that oil reserves are controlled by a relatively small number of countries who have it within their capacity to attempt to control United States foreign policies by regulating prices and amounts of oil exports to the U.S. This would be an unacceptable situation, and to avoid its occurrence, the United States is embarking on "Project Independence," a program intended to diversify our energy sources over the next decade so that no large segment will be under the control of a single foreign government or even an alliance of governments.

Energy independence can be accomplished through a program of conservation of liquid and gaseous hydrocarbon fuels and of substitution of other, more abundant native energy sources for applications where the transportability of liquid and gaseous hydrocarbons is not an essential property. Abundant reserves of energy are available in the United States in the form of coal, oil shale, earth heat, and solar insolation. Each of these alternative energy sources has distinct technological problems involved in its increased development, and each will have some characteristic effect on the environment which will have to be considered and accepted. However, it is likely that all these alternate energy sources will be developed to provide a diversified, reliable energy base for the country.

The subject of this report is one of these alternate energy sources, geothermal energy. The interior of the earth is at a very high temperature, thousands of degrees Kelvin. This heat energy is probably the remnants of the original energy of formation of the earth, supplemented by heat from the decay of radioactive elements. This heat energy escapes slowly through the earth's crust, and is then lost to space. The rate of escape, averaged over the earth's entire surface, is approximately 1.5 microcalories per square centimeter. This amount of energy flowing from the land area of the United States could provide the 2 kilowatts of electrical generating capacity now required by each of our citizens, if the heat energy could be totally converted to electricity with 100% efficiency. In fact, the efficiency for conversion of heat to electricity is quite low, and the continuous flow of heat from the earth does not comprise the most attractive form of geothermal energy.

Where geothermal energy is now being used to generate electricity, as at Wairaki, in New Zealand, the Geysers in California, Lardarello, in Italy, and Cerro Prieto, in Mexico, very high temperatures have been brought close to the surface of the earth by various geological processes which are capable of transporting heat from the deep interior of the earth. To be worthy of development, a high-grade geothermal system should have temperatures above $200^{\circ}C$ within one or two kilometers of the earth's surface, so that they can be reached by drilling a borehole at reasonable cost. Moreover, the heated rock should contain large amounts of water in pore spaces, so that the water can be used as a heat exchange medium to extract heat easily from rock. Thus, a high-grade geothermal reservoir can be thought of as being a water-laden permeable rock section, heated from beneath by a shallow intrusive or other heat source.

In developing geothermal energy, the first step is to prospect for high-grade geothermal reservoirs of the type just described. This is done using the geochemical, geological, and geophysical techniques described in a later section. Once evidence has been found for the presence of a geothermal reservoir, its existence must be proven by drilling a test well to confirm that adequate temperatures and flow rates can be obtained. Only then can development drilling be undertaken and a plant for utilizing the energy be planned.

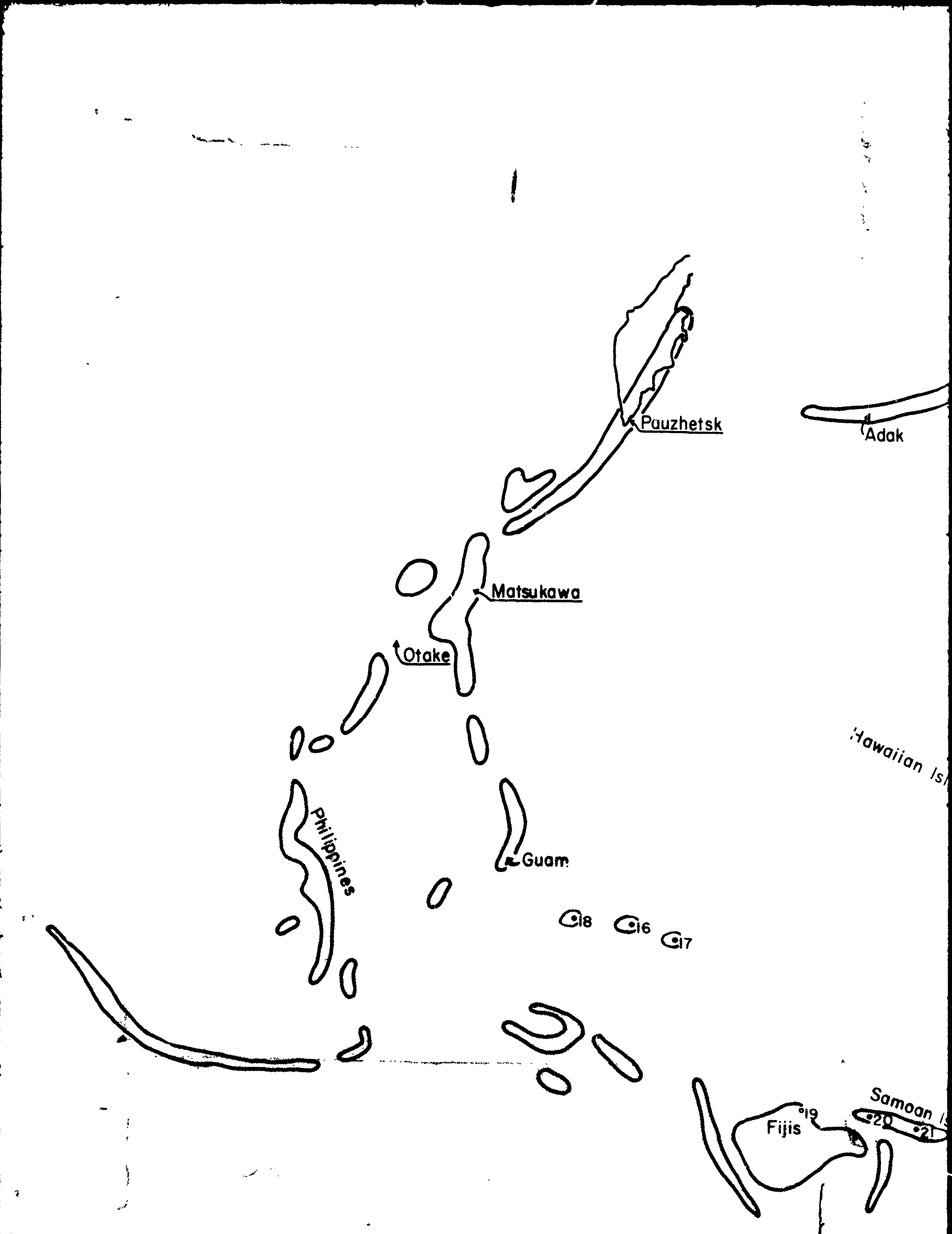
Existing geothermal plants have been built because geothermal energy can be used at those locations to generate electricity more cheaply than any other energy costs. The costs for developing geothermal energy are as follows:

1. Exploration. The cost of geochemical, geological and geophysical exploration is small compared with other costs in developing a geothermal

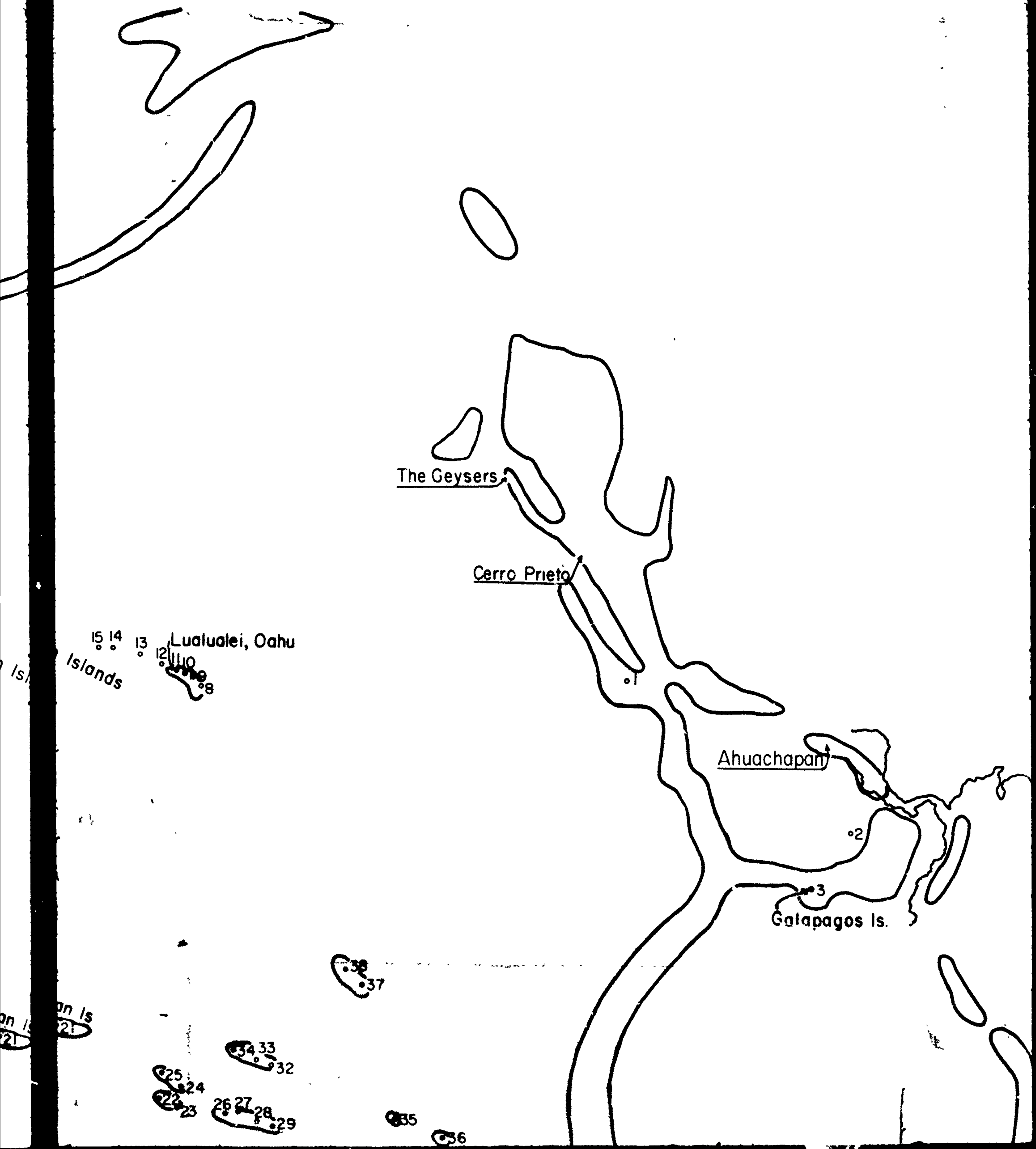
any other energy costs. The costs for developing geothermal energy are as follows:

1. Exploration. The cost of geochemical, geological and geophysical exploration is small compared with other costs in developing a geothermal system. Exploration may cost as little as $20,000 per prospect, if the prospect is a very obvious one, requiring only a modicum of work to pinpoint a location for a test well, or as much as $200,000 per prospect, if the prospect is less obvious. Likewise, the cost of drilling a test hole can vary widely, depending on difficulties met in drilling, depth drilled, and remoteness of the site. Under the most favorable conditions, a geothermal test well would cost a minimum of $250,000. Under less favorable conditions, test wells can cost in excess of $1,000,000, as several drilled in the United States during the last year have. Thus, exploration and test drilling of a single geothermal prospect will normally cost at least one quarter million dollars, and may cost as much as 1½ million dollars. In an overall program, this cost for testing a single geothermal prospect, F, must be multiplied by a factor N_F representing the ratio of the total number of prospects tested to the number found to be producible, to distribute the costs of unsuccessful tests over the successful prospects. Not enough experience is available to provide a value for N_F, the failure rate, based on experience. The value has been estimated to be as low as unity (by representatives of the United Nations Geothermal Program) to as high as 8 (by a representative of a major U.S. oil company engaged in geothermal prospecting). The value for this failure ratio will depend strongly on the expertise of the people involved in selecting prospects.

2. Development Drilling. Once the presence of a producible geothermal reservoir has been verified by a successful test hole, it is necessary to drill a number of wells to provide the required amount of energy. If electricity is to be generated, the quality of the steam produced from the geothermal reservoir is measured in terms of the number of pounds of steam required to generate a kilowatt-hour (or unit) of electricity. The "steam quality" for presently producing geothermal fields is in the neighborhood of 20 to 22 pounds, so that if a well produces 100,000 pounds of steam per hour, this amount of production can support a 5 megawatt generator capacity. Average production capacities for individual wells at presently productive geothermal fields is in the range 60,000 to 100,000 pounds of steam, though a few wells will produce at much higher rates, up to 500,000 pounds of steam per hour. There is no lower limit on production rate except that imposed by economic considerations; it is unlikely that wells with flow rates lower than 20,000 pounds per hour (1 megawatt electrical generating capacity) would be connected into a steam gathering system.


Pauzhetsk
Adak
Matsukawa
Otake
Hawaiian Isl
Philippines
Guam
18
16
17
Samoan Is
19
Fijis
20
21

2


The Geysers
Cerro Prieto
Lualualei, Oahu
Islands
Ahuachapan
Galapagos Is.
1
2
3
8
10
11
12
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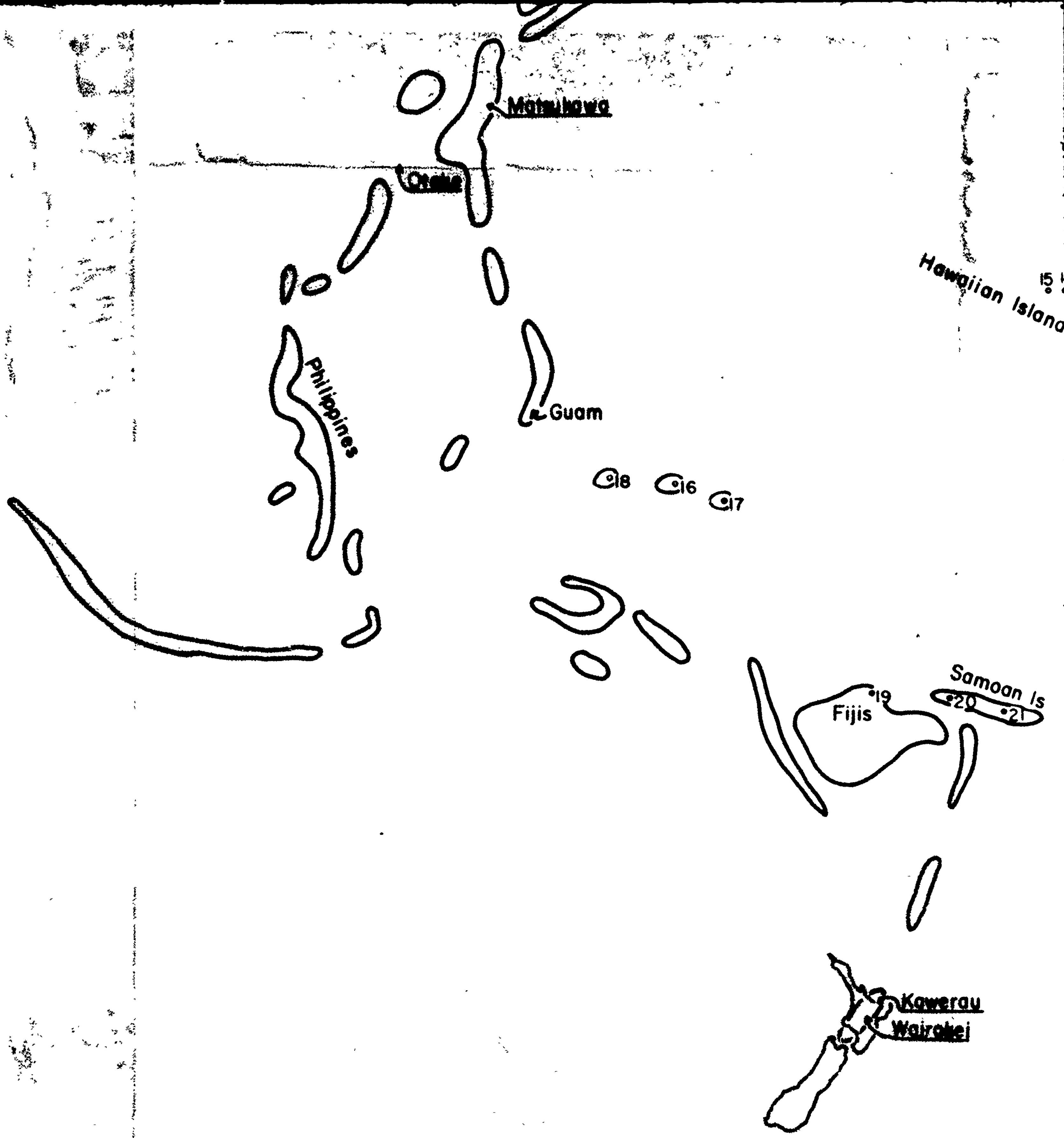

Matsukawa
Otake
Hawaiian Island
15
Philippines
Guam
18
16
17
Samoan Is
19
20
21
Fijis
Kawerau
Wairakei

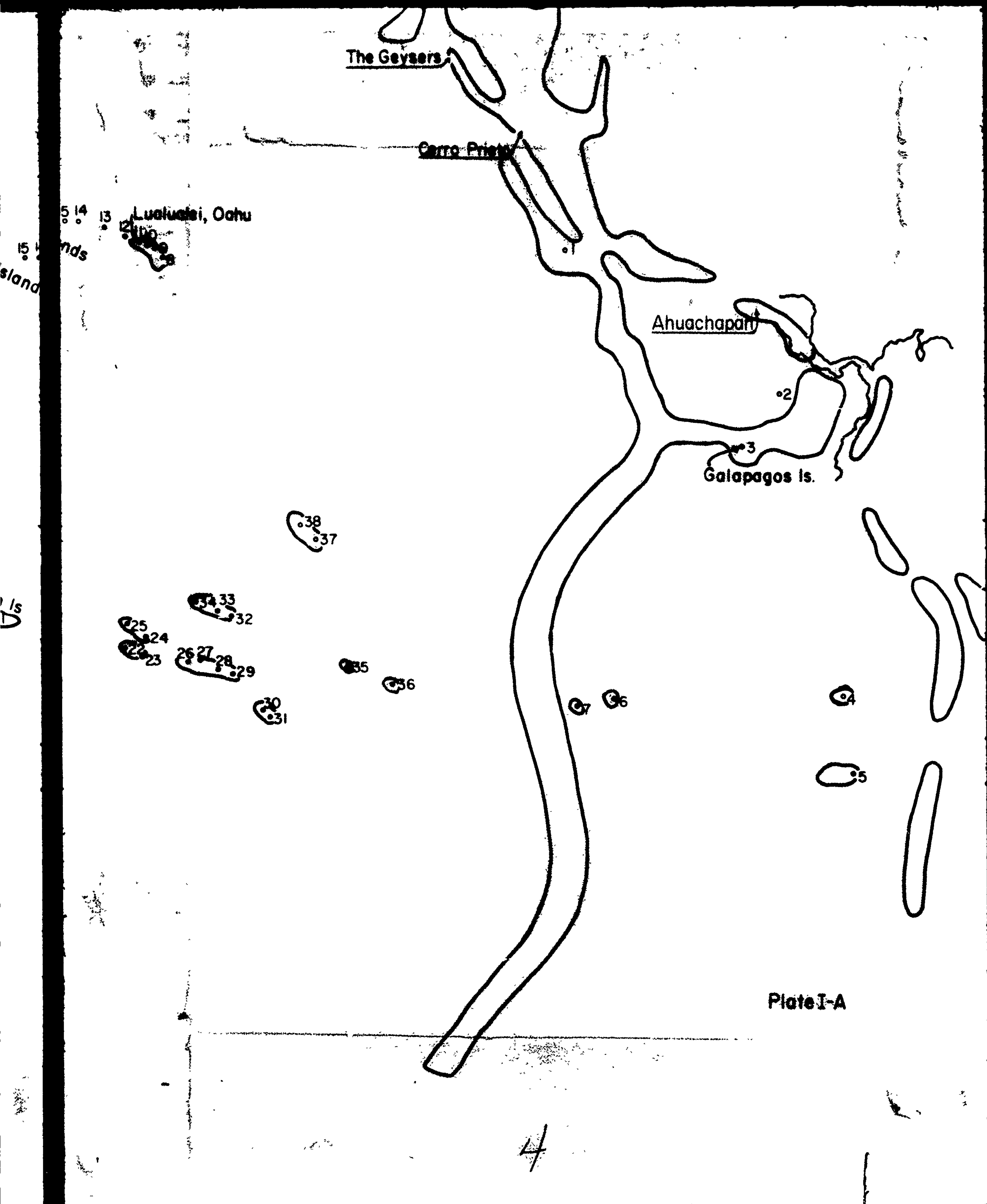
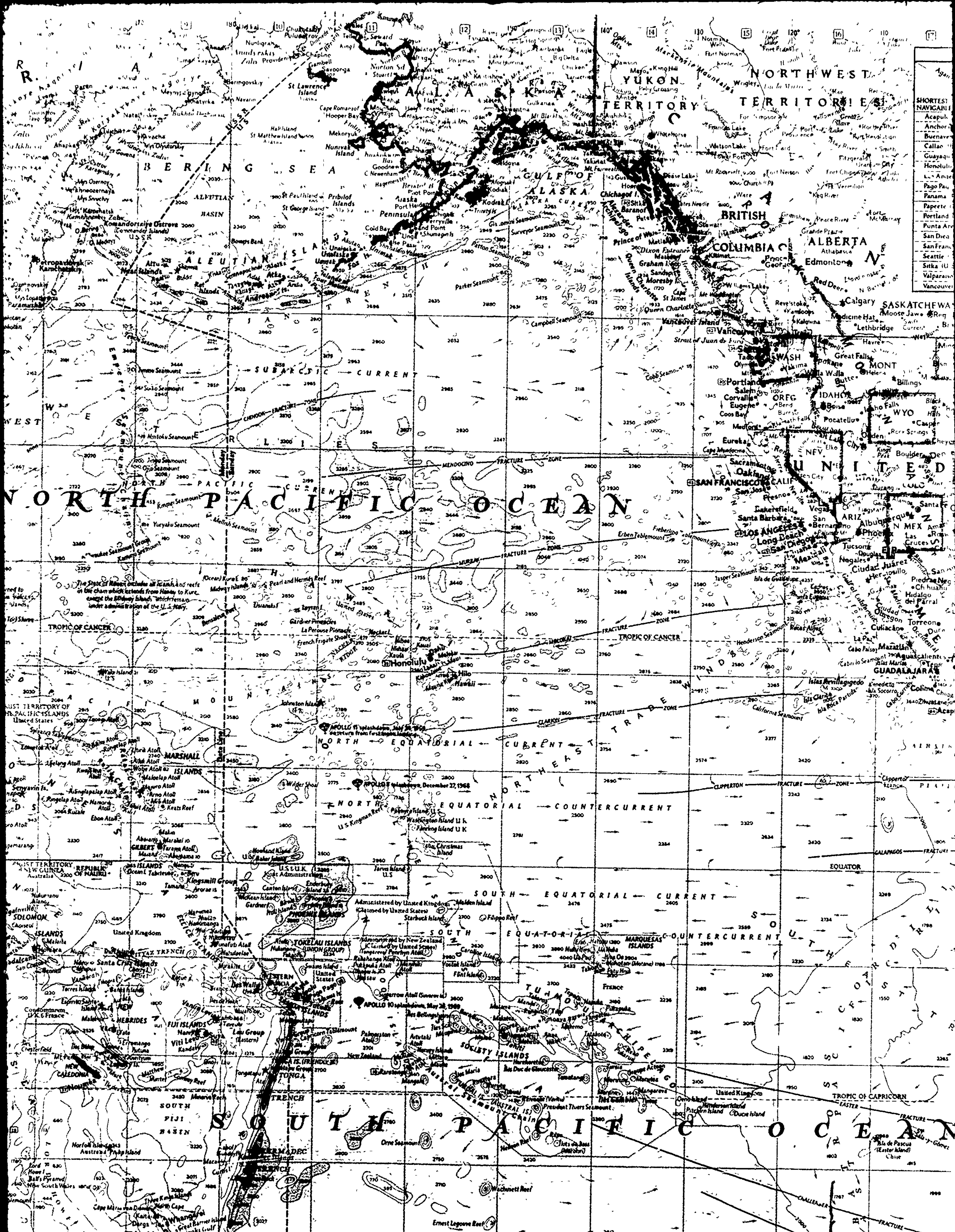
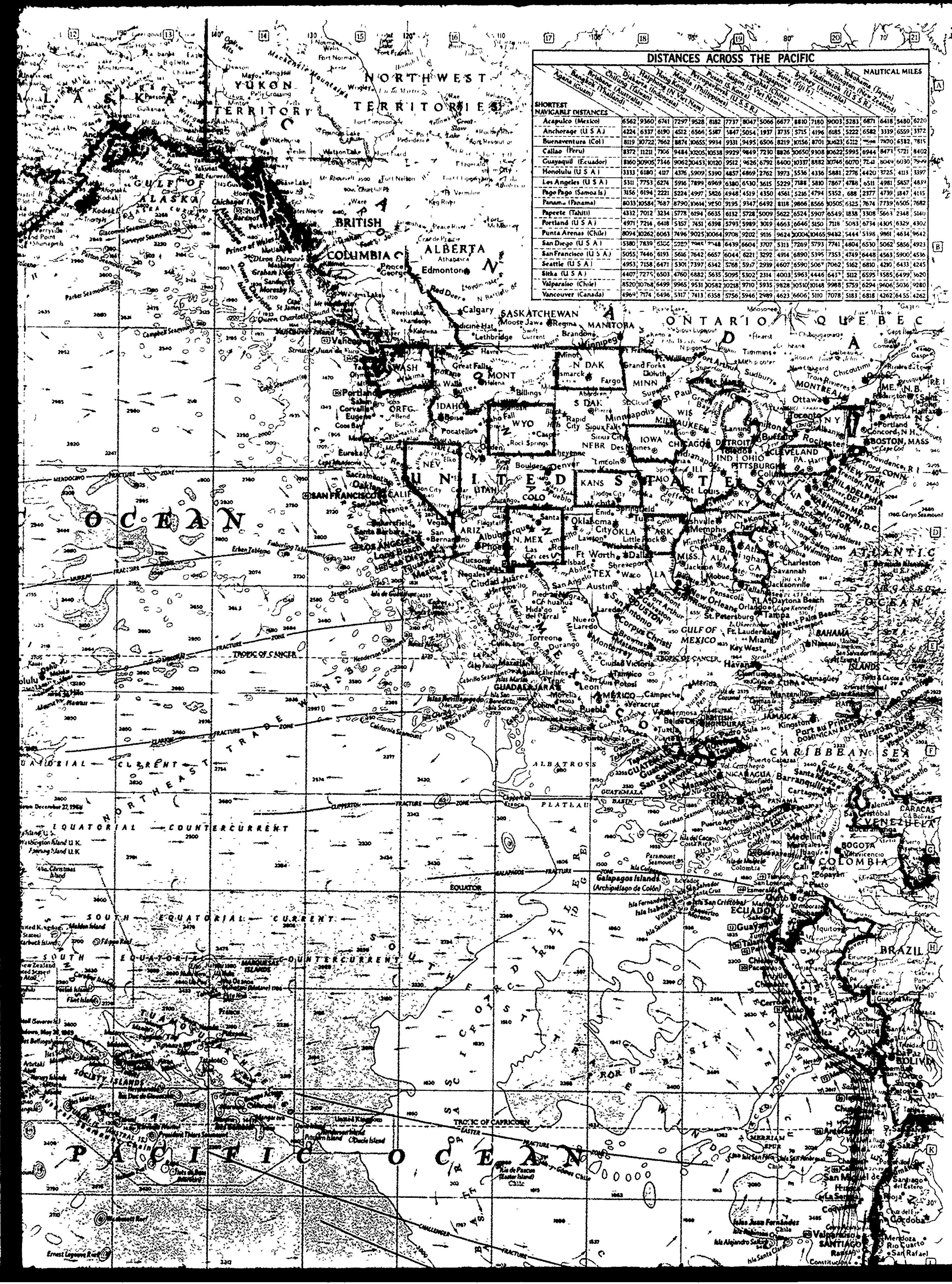

The Geysers
Cerro Prieto
Lualualei, Oahu
Ahuachapan
Galapagos Is.

Plate I-A


PACIFIC OCEAN
Compiled and Drawn in the Cartographic Division of the
National Geographic Society
for THE NATIONAL GEOGRAPHIC MAGAZINE
SCALE 1:36,432,000 OR 575 MILES TO THE INCH AT THE EQUATOR
MONGOLIAN REPUBLIC
CHINA
JAPAN
KOREA
PHILIPPINES
NORTH PACIFIC
SEA OF OKHOTSK
BERING SEA
ALEUTIAN ISLANDS
KAMCHATKA
SAKHALIN
HOKKAIDO
PHILIPPINE SEA
MARSHALL ISLANDS
CAROLINE ISLANDS
GREATER SUNDA ISLANDS
INDONESIA
NEW GUINEA
SOLOMON ISLANDS
CORAL SEA
NEW HEBRIDES
FIJI ISLANDS
NEW CALEDONIA
TONGA
AUSTRALIA
WESTERN AUSTRALIA
NORTHERN TERRITORY
QUEENSLAND
SOUTH AUSTRALIA
NEW SOUTH WALES
TROPIC OF CANCER
TROPIC OF CAPRICORN
SHANGHAI
TOKYO
SYDNEY



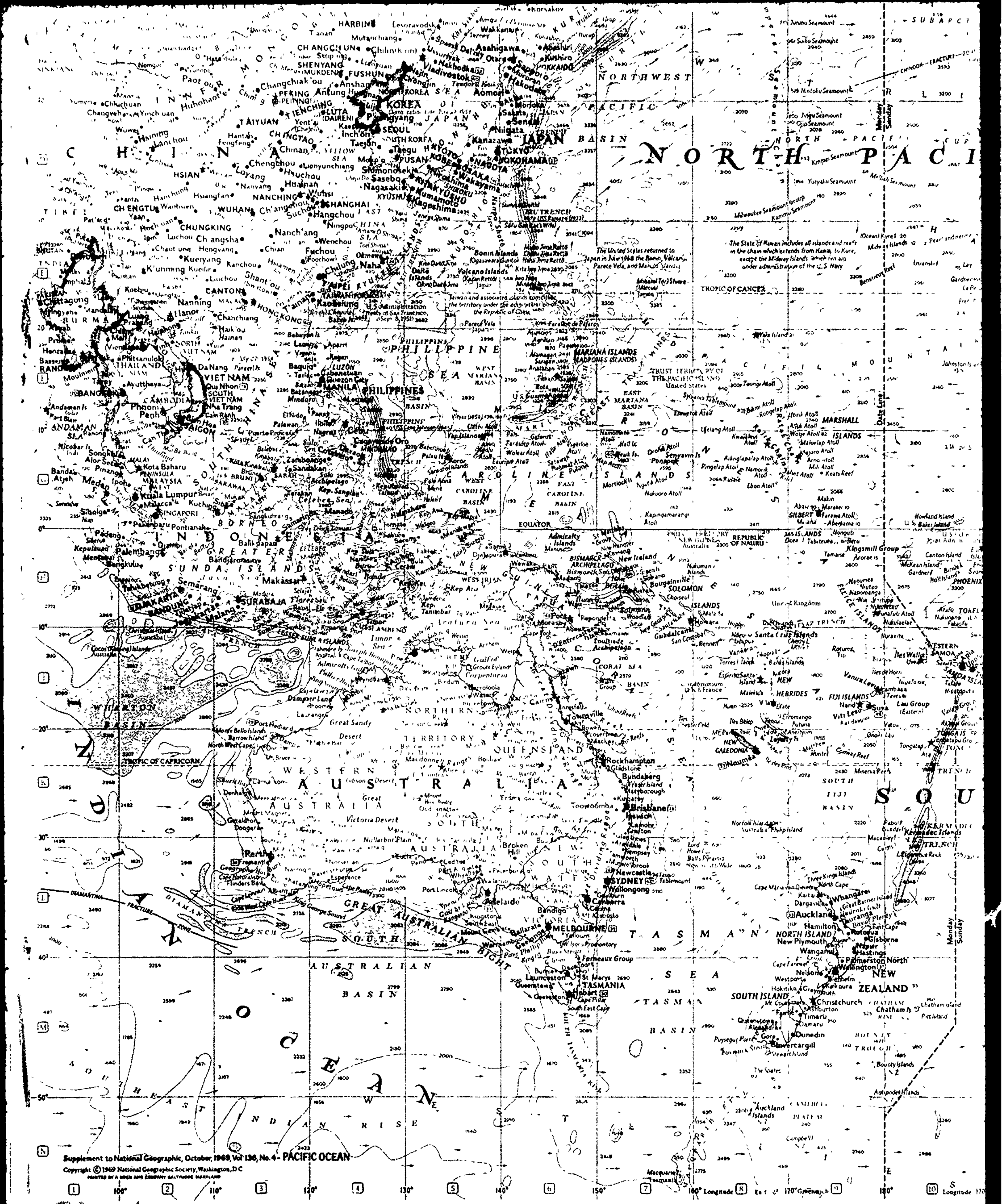
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
BERING SEA
ALASKA
GULF OF ALASKA
YUKON TERRITORY
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
WASH
OREG
IDAHO
MONT
WYO
NEV
CALIF
ARIZ
N MEX
UNITED
ALEUTIAN ISLANDS
ALEUTIAN BASIN
SUBARCTIC CURRENT
NORTH PACIFIC CURRENT
NORTH EQUATORIAL CURRENT
NORTH EQUATORIAL COUNTERCURRENT
SOUTH EQUATORIAL CURRENT
SOUTH EQUATORIAL COUNTERCURRENT
NORTHEAST TRADE WINDS
TROPIC OF CANCER
EQUATOR
TROPIC OF CAPRICORN
MENDOCINO FRACTURE ZONE
MURRAY FRACTURE ZONE
MOLOKAI FRACTURE ZONE
CLARION FRACTURE ZONE
CLIPPERTON FRACTURE ZONE
CHINOOK FRACTURE ZONE
GALAPAGOS FRACTURE ZONE
Kodiak
Anchorage
St Lawrence Island
Nunivak Island
Komandorskiye Ostrova (Commander Islands)
Petropavlovsk Kamchatskiy
Vancouver
Vancouver Island
Seattle
Portland
SAN FRANCISCO
Sacramento
LOS ANGELES
San Diego
Long Beach
Calgary
Edmonton
Honolulu
Hawaii
Hilo
Midway Islands
Johnston Island
MARSHALL ISLANDS
GILBERT ISLANDS
PHOENIX ISLANDS
TOKELAU ISLANDS
SOLOMON ISLANDS
NEW HEBRIDES
FIJI ISLANDS
TONGA
SOCIETY ISLANDS
Tahiti
MARQUESAS ISLANDS
TUAMOTU ARCHIPELAGO
KERMADEC TRENCH
SOUTH FIJI BASIN
Auckland
Whangarei
Norfolk Island
New Caledonia
Noumea
Pitcairn Island
Isla de Pascua (Easter Island)
APOLLO 8 splashdown, December 27, 1968
APOLLO 10 splashdown, May 26, 1969
APOLLO 11 splashdown, July 24, 1969
Administered by United Kingdom
Ciudad Juárez
Chihuahua
Mazatlán
GUADALAJARA
Torreón
Culiacán
Hermosillo
Tucson
Albuquerque
Mexicali
Ensenada



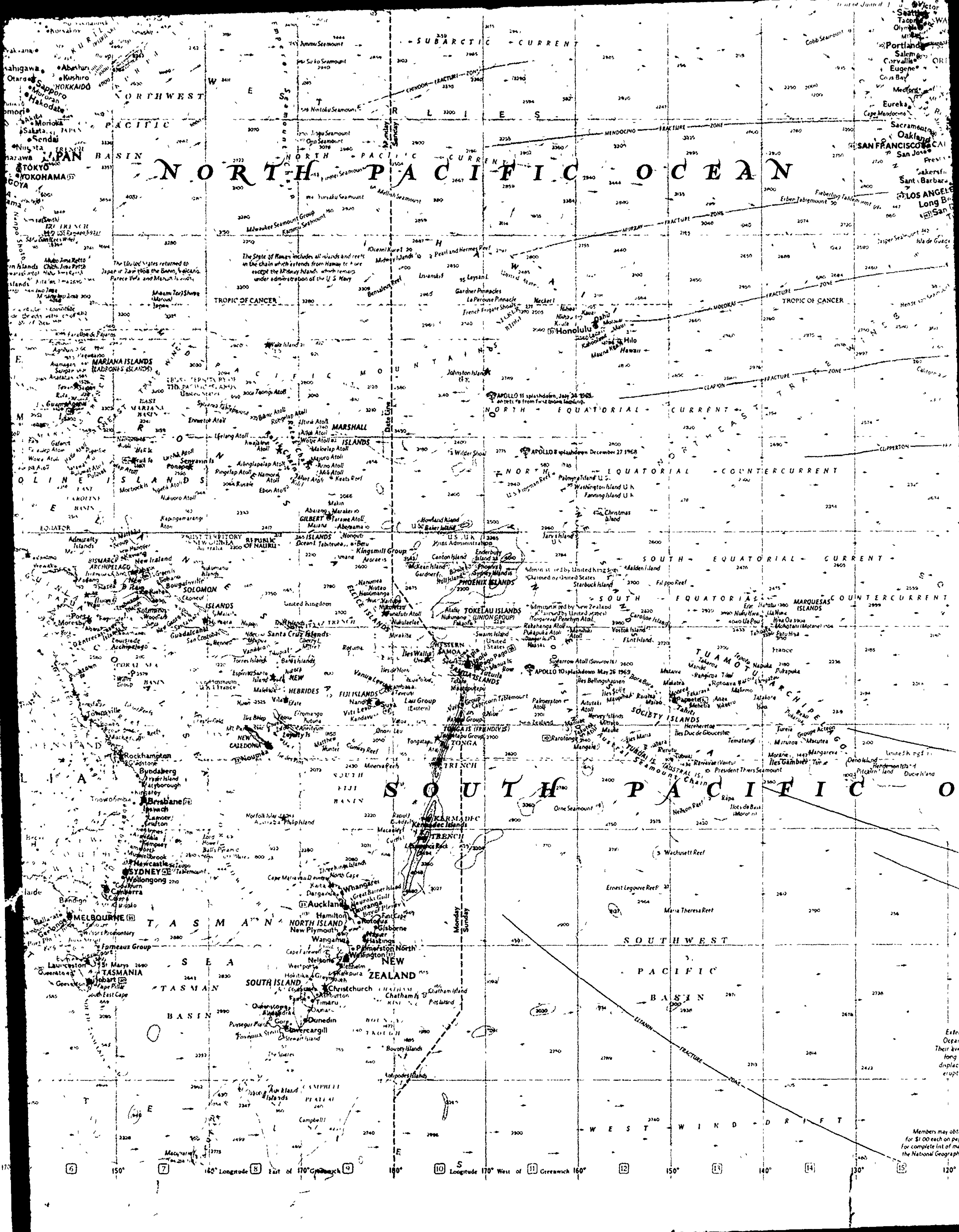
DISTANCES ACROSS THE PACIFIC

NAUTICAL MILES

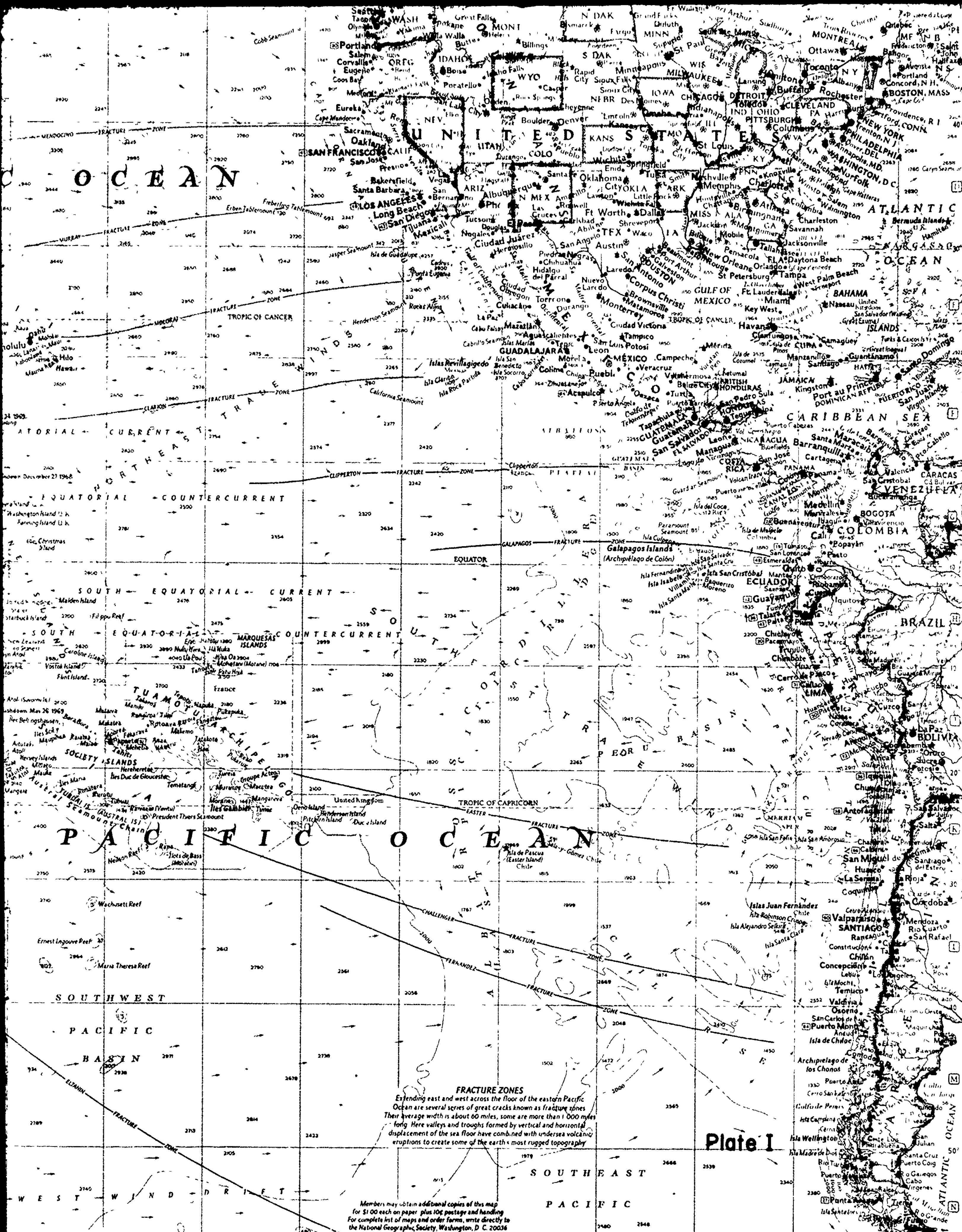
SHORTEST NAVIGABLE DISTANCES	Agana (Guam)	Bangkok (Thailand)	Brisbane (Australia)	Chilung (Taiwan)	Djakarta (Indonesia)	Haiphong (N Viet Nam)	Hong Kong	Manila (Philippines)	Petropavlovsk (U S S R)	Pusan (S Korea)	Saigon (S Viet Nam)	Shanghai (China)	Singapore	Suva (Fiji Is)	Sydney (Australia)	Vladivostok (U S S R)	Wellington (New Zealand)	Yokohama (Japan)
Acapulco (Mexico)	6562	9360	6741	7297	9528	8182	7737	8047	5066	6677	8810	7180	9003	5283	6871	6418	5480	6220
Anchorage (U S A)	4224	6337	6190	4512	6566	5387	4847	5054	1937	3735	5715	4196	6185	5222	6582	3339	6559	3372
Buenaventura (Col)	8119	10722	7662	8874	10655	9934	9331	9495	6506	8219	10156	8701	10623	6322	[illegible]	7870	6382	7815
Callao (Peru)	8372	11211	7106	9484	10205	10538	9929	9849	7230	8826	10650	9308	10622	5995	6944	8471	5721	8402
Guayaquil (Ecuador)	8160	10905	7346	9062	10453	10120	9512	9626	6792	8400	10337	8882	10746	6070	7241	8049	6030	7949
Honolulu (U S A)	3333	6180	4117	4376	5909	5390	4857	4869	2762	3973	5536	4336	5881	2776	4420	3725	4113	3397
Los Angeles (U S A)	5311	7753	6274	5916	7899	6969	6380	6530	3615	5229	7188	5810	7867	4788	6511	4981	5857	4839
Pago Pago (Samoa Is)	3156	6194	2221	5224	4997	5426	4948	4519	4350	4561	5216	4794	5352	688	2377	4739	1847	4135
Panama (Panama)	8033	10584	7687	8790	10614	9250	9195	9347	6492	8118	9866	8566	10505	6325	7674	7739	6505	7682
Papeete (Tahiti)	4332	7012	3234	5778	6194	6635	6132	5728	5009	5622	6524	5907	6549	1838	3308	5663	2348	5140
Portland (U S A)	4971	7214	6418	5357	7451	6398	5793	5989	3019	4663	6646	5150	7118	5083	6734	4305	6329	4302
Punta Arenas (Chile)	8094	10262	6063	7496	9025	10064	9708	9202	9116	9624	10004	10465	9482	5444	5398	9861	4634	9642
San Diego (U S A)	5380	7839	6300	5929	7985	7148	6439	6604	3707	5313	7269	5793	7741	4804	6530	5062	5856	4923
San Francisco (U S A)	5055	7446	6193	5616	7642	6657	6044	6221	3292	4914	6890	5395	7353	4749	6448	4563	5900	4536
Seattle (U S A)	4953	7158	6471	5301	7397	6342	5768	5937	2939	4607	6590	5067	7062	5162	6810	4210	6433	4245
Sitka (U S A)	4407	7275	6503	4760	6882	5635	5095	5302	2314	4003	5963	4446	6437	5112	6595	3585	6499	3620
Valparaiso (Chile)	8520	10768	6499	9965	9531	10582	10218	9710	5935	9828	10510	10148	9988	5759	6294	9606	5036	9280
Vancouver (Canada)	4969	7174	6496	5317	7413	6358	5756	5946	2989	4623	6606	5110	7078	5183	6818	4262	6455	4262



Supplement to National Geographic, October, 1969, Vol 136, No. 4 - PACIFIC OCEAN

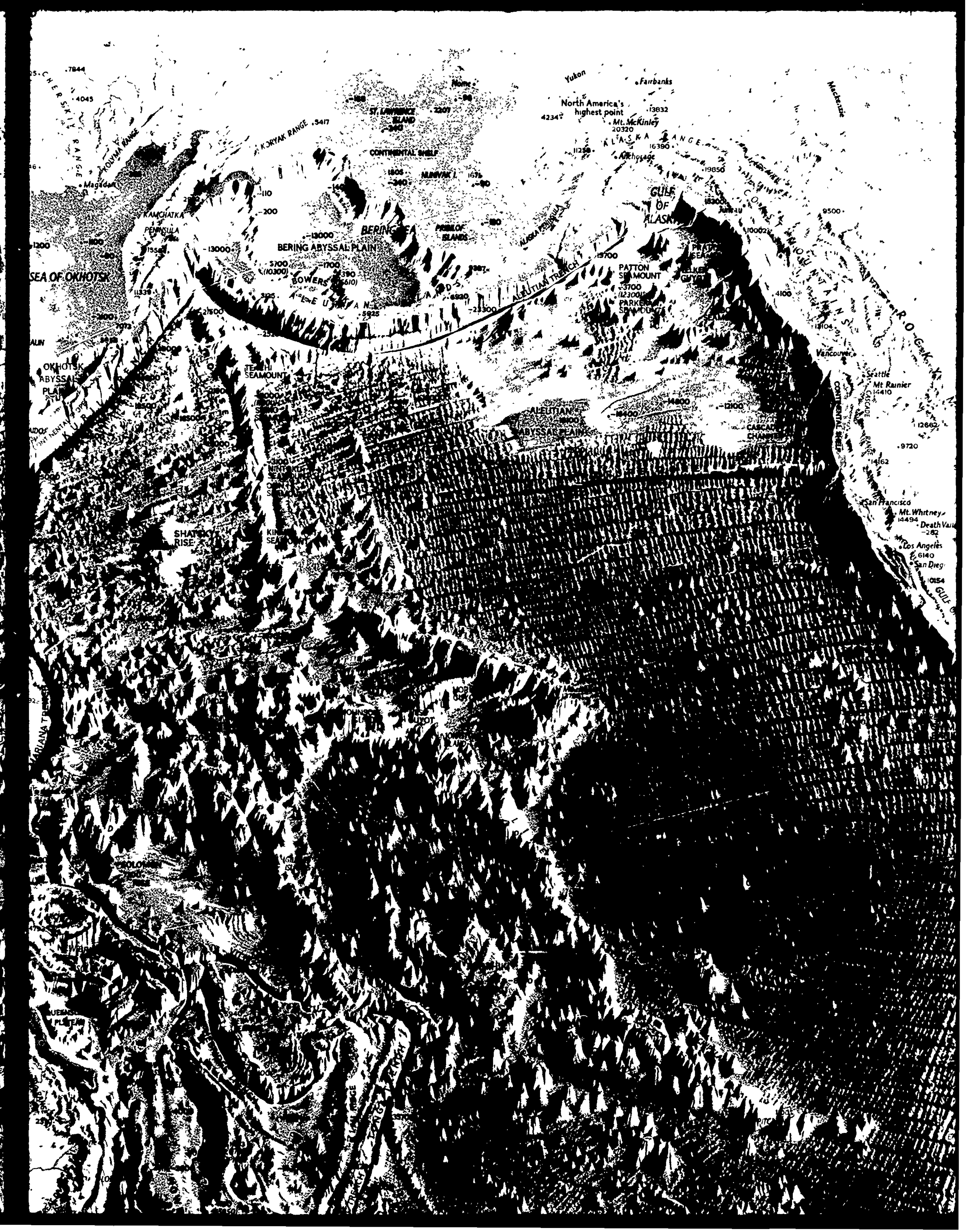


NORTH PACIFIC OCEAN
SOUTH PACIFIC O
SUBARCTIC CURRENT
NORTH PACIFIC CURRENT
NORTH EQUATORIAL CURRENT
NORTH EQUATORIAL COUNTERCURRENT
SOUTH EQUATORIAL CURRENT
SOUTH EQUATORIAL COUNTERCURRENT
WEST WIND DRIFT
NORTHWEST PACIFIC BASIN
SOUTHWEST PACIFIC BASIN
TASMAN SEA
TASMAN BASIN
CORAL SEA
SOUTH FIJI BASIN
TROPIC OF CANCER
EQUATOR
Date Line
Monday Sunday
MENDOCINO FRACTURE ZONE
MURRAY FRACTURE ZONE
MOLOKAI FRACTURE ZONE
CLARION FRACTURE ZONE
CLIPPERTON
ELTANIN FRACTURE ZONE
KERMADEC TRENCH
TONGA TRENCH
The State of Hawaii includes all islands and reefs in the chain which extends from Hawaii to Kure except the Midway Islands, which remain under administration of the U.S. Navy
The United States returned to Japan in 1968 the Bonin, Volcano, Parece Vela and Marcus Islands
APOLLO 11 splashdown, July 24 1969
APOLLO 8 splashdown December 27 1968
APOLLO 10 splashdown May 26 1969
Honolulu
Oahu
Kauai
Maui
Hawaii
Hilo
Midway Islands
Laysan I.
Johnston Island
MARIANA ISLANDS
MARSHALL ISLANDS
GILBERT ISLANDS
PHOENIX ISLANDS
TOKELAU ISLANDS
ELLICE ISLANDS
SOLOMON ISLANDS
Santa Cruz Islands
NEW HEBRIDES
NEW CALEDONIA
Nouméa
FIJI ISLANDS
Lau Group
TONGA
WESTERN SAMOA
Pago Pago
Rarotonga
SOCIETY ISLANDS
Papeete
Tahiti
TUAMOTU ARCHIPELAGO
MARQUESAS ISLANDS
Christmas Island
Palmyra Island
Fanning Island
Jarvis Island
Malden Island
Starbuck Island
Canton Island
Howland Island
Baker Island
REPUBLIC OF NAURU
New Ireland
BISMARCK ARCHIPELAGO
Bougainville
Guadalcanal
Port Moresby
Norfolk Island
Lord Howe I.
Kermadec Islands
NEW ZEALAND
NORTH ISLAND
SOUTH ISLAND
Auckland
Hamilton
New Plymouth
Wanganui
Napier
Hastings
Gisborne
Palmerston North
Wellington
Nelson
Christchurch
Timaru
Dunedin
Invercargill
Chatham Is.
Bounty Islands
Antipodes Islands
Auckland Islands
Campbell I.
Macquarie I.
SYDNEY
Newcastle
Wollongong
Canberra
MELBOURNE
Brisbane
Bundaberg
Rockhampton
Townsville
Toowoomba
Geelong
Ballarat
Bendigo
TASMANIA
Hobart
Launceston
Furneaux Group
JAPAN
TOKYO
YOKOHAMA
Sendai
Sapporo
Hakodate
HOKKAIDO
Seattle
Portland
Salem
Eugene
Eureka
Sacramento
Oakland
SAN FRANCISCO
San Jose
LOS ANGELES
Long Beach
Members may obtain a ... for $1.00 each on paper ... For complete list of maps an... the National Geographic Soc...
150°
160° Longitude East of 170° Greenwich
180°
Longitude 170° West of Greenwich 160°
150°
140°
130°
120°



PACIFIC OCEAN
ATLANTIC OCEAN
SARGASSO OCEAN
CARIBBEAN SEA
GULF OF MEXICO
UNITED STATES
MEXICO
COLOMBIA
VENEZUELA
BRAZIL
BOLIVIA
ECUADOR
TROPIC OF CANCER
EQUATOR
TROPIC OF CAPRICORN
NORTHEAST TRADE WINDS
EQUATORIAL COUNTERCURRENT
SOUTH EQUATORIAL CURRENT
SOUTH EQUATORIAL COUNTERCURRENT
SOUTHWEST PACIFIC BASIN
SOUTHEAST PACIFIC BASIN
WEST WIND DRIFT
Galapagos Islands
(Archipiélago de Colón)
TUAMOTU ARCHIPELAGO
SOCIETY ISLANDS
MARQUESAS ISLANDS
MENDOCINO FRACTURE ZONE
MURRAY FRACTURE ZONE
MOLOKAI FRACTURE ZONE
CLARION FRACTURE ZONE
CLIPPERTON FRACTURE ZONE
GALAPAGOS FRACTURE ZONE
EASTER FRACTURE ZONE
CHALLENGER FRACTURE ZONE
FERNANDEZ FRACTURE ZONE
ELTANIN FRACTURE ZONE
FRACTURE ZONES
Extending east and west across the floor of the eastern Pacific Ocean are several series of great cracks known as fracture zones Their average width is about 60 miles, some are more than 1 000 miles long Here valleys and troughs formed by vertical and horizontal displacement of the sea floor have combined with undersea volcanic eruptions to create some of the earth's most rugged topography
Members may obtain additional copies of this map for $1 00 each on paper plus 10¢ postage and handling For complete list of maps and order forms, write directly to the National Geographic Society, Washington, D C. 20036
Plate I

SIBERIA
CENTRAL SIBERIAN PLATEAU
Angara
Lena
Bratsk Reservoir
LAKE BAYKAL
World's deepest lake 5,315 feet
Ulan Bator
ASIA
MONGOLIAN PLATEAU
ALTAI MOUNTAINS
GOBI
GREATER KHINGAN RANGE
MANCHURIAN PLAIN
Amur
Vladivostok
Peking
SEA OF JAPAN
HONSHU
JAPAN
Tokyo
Shanghai
Yangtze
Hong Kong
Hanoi
Luang Prabang
Vientiane
Rangoon
INDOCHINA PENINSULA
Bangkok
Saigon
ANDAMAN ISLANDS
SEA OF OKHOTSK
KAMCHATKA PENINSULA
KORYAK RANGE
BERING SEA
BERING ABYSSAL PLAIN
ST. LAWRENCE ISLAND
JAPAN TRENCH
SHATSKY RISE
Perth
AUSTRALIA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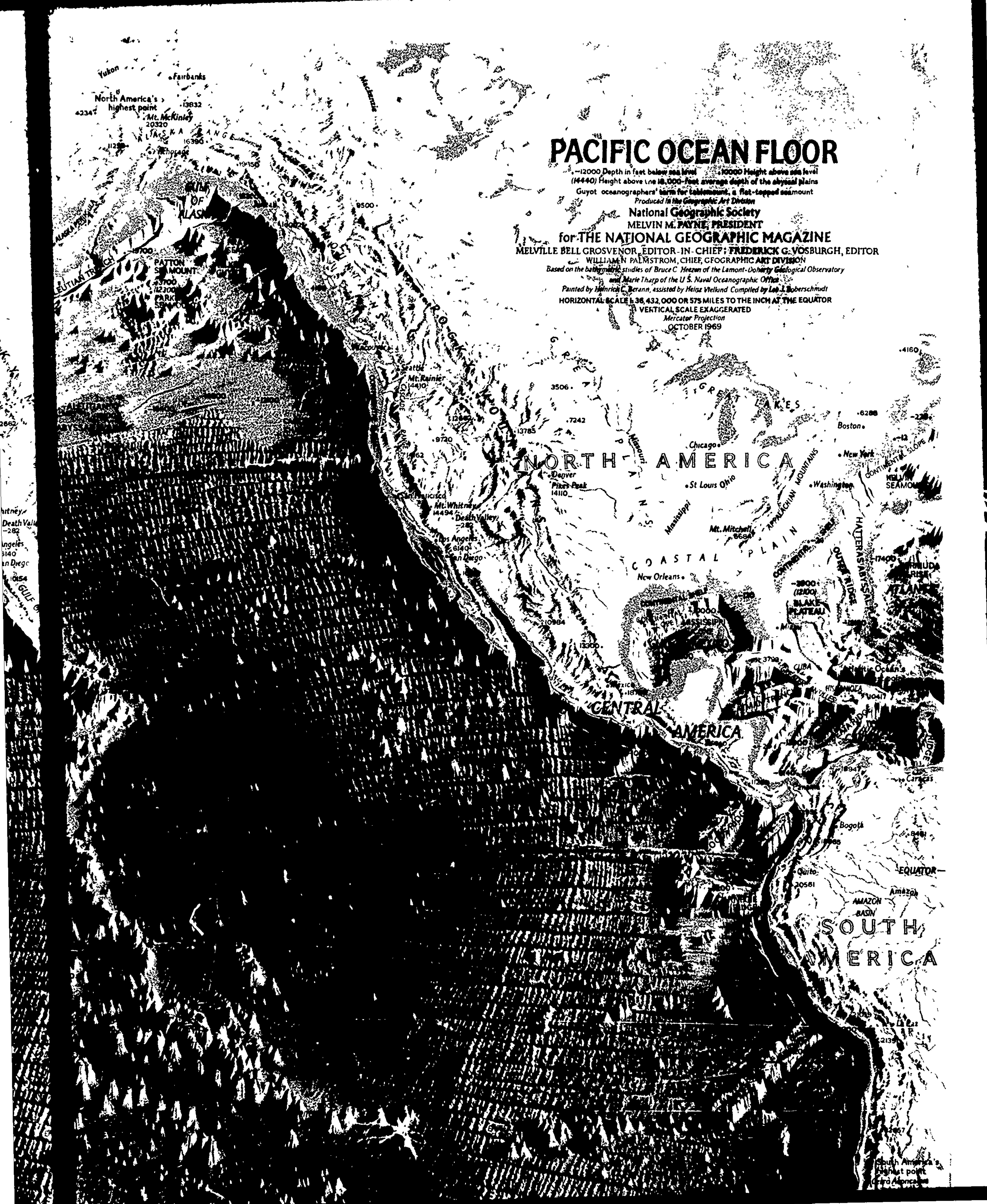
PACIFIC OCEAN FLOOR
-12000 Depth in feet below sea level
10000 Height above sea level
(14440) Height above the 18,000-foot average depth of the abyssal plains
Guyot oceanographers' term for tablemount, a flat-topped seamount
Produced in the Geographic Art Division
National Geographic Society
MELVIN M. PAYNE, PRESIDENT
for THE NATIONAL GEOGRAPHIC MAGAZINE
MELVILLE BELL GROSVENOR, EDITOR-IN-CHIEF; FREDERICK G. VOSBURGH, EDITOR
WILLIAM N. PALMSTROM, CHIEF, GEOGRAPHIC ART DIVISION
Based on the bathymetric studies of Bruce C. Heezen of the Lamont-Doherty Geological Observatory
and Marie Tharp of the U.S. Naval Oceanographic Office
Painted by Heinrich C. Berann, assisted by Heinz Vielkind. Compiled by Leo J. Roberschmidt
HORIZONTAL SCALE 1:36,432,000 OR 575 MILES TO THE INCH AT THE EQUATOR
VERTICAL SCALE EXAGGERATED
Mercator Projection
OCTOBER 1969
Yukon
Fairbanks
North America's highest point
Mt. McKinley
20320
GULF OF ALASKA
PATTON SEAMOUNT
Seattle
Mt. Rainier
GREAT LAKES
Boston
Chicago
NORTH AMERICA
New York
Denver
Pikes Peak
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Mt. Whitney
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Death Valley
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Los Angeles
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Mississippi
Mt. Mitchell
COASTAL PLAIN
New Orleans
BLAKE PLATEAU
CUBA
CENTRAL AMERICA
Caracas
Bogotá
Quito
EQUATOR
Amazon
AMAZON BASIN
SOUTH AMERICA
South America's highest point

MONGOLIAN PLATEAU
GOBI
NAN SHAN
MANCHURIAN PLAIN
Vladivostok
HOKKAIDO
Peking
SEA OF JAPAN
Seoul
HONSHU
JAPAN
JAPAN TRENCH
Shanghai
Yangtze
EAST CHINA SEA
Minya Konka
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Hong Kong
Hanoi
Vientiane
INDOCHINA PENINSULA
Bangkok
Saigon
MACCLESFIELD BANK
LUZON
SOUTH CHINA SEA
Singapore
BORNEO
CELEBES
GREATER SUNDA
JAVA
NEW GUINEA
SOLOMON
Darwin
AUSTRALIA
Perth
Darling
Murray
Australia's highest point
Mt. Kosciusko
Melbourne
TASMANIA
Hobart
BROKEN RIDGE
NEW ZEALAND
Wellington
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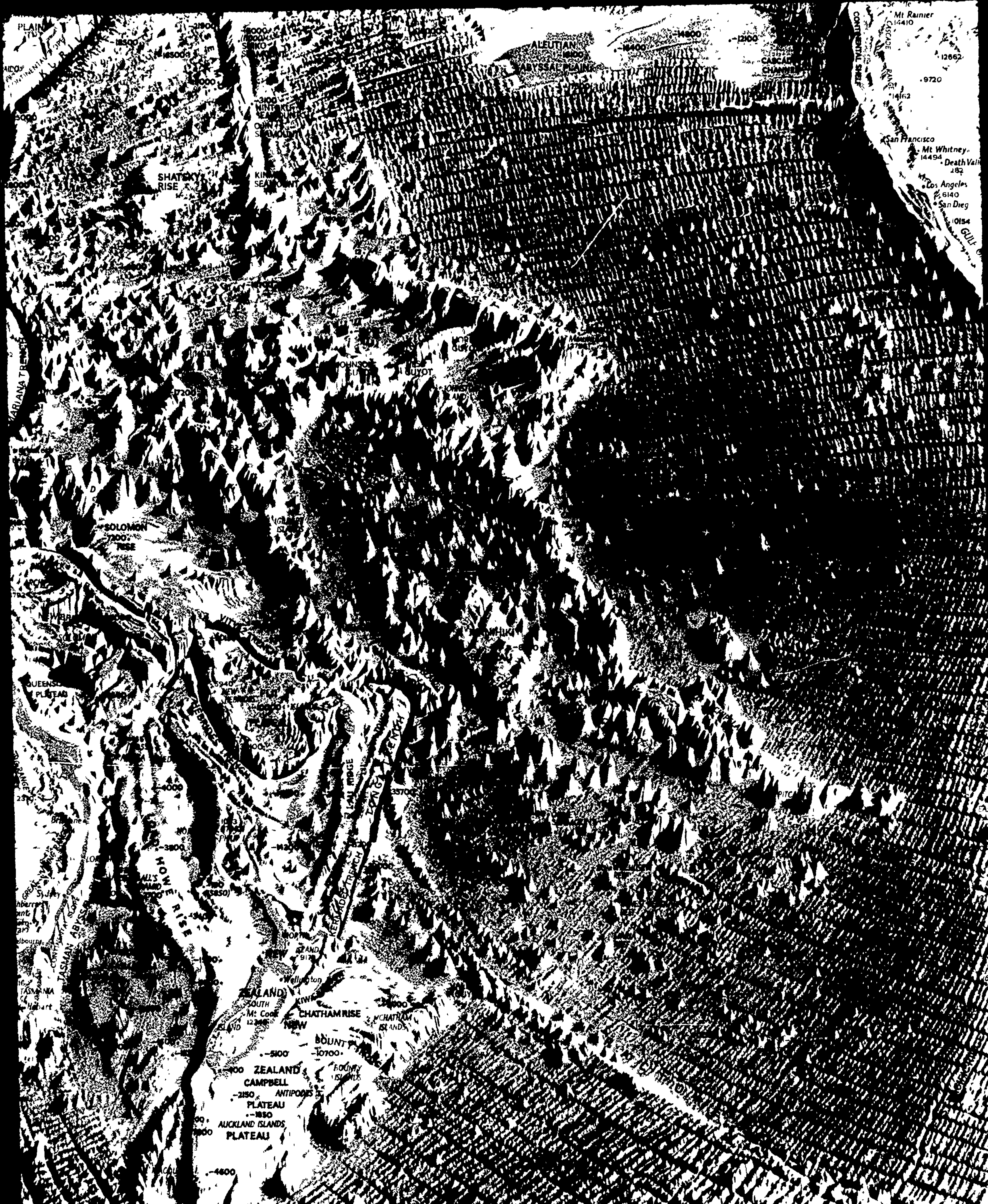

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HOWE RISE
TONGA TRENCH
KERMADEC TRENCH
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ZEALAND
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CHATHAM RISE
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ISLANDS
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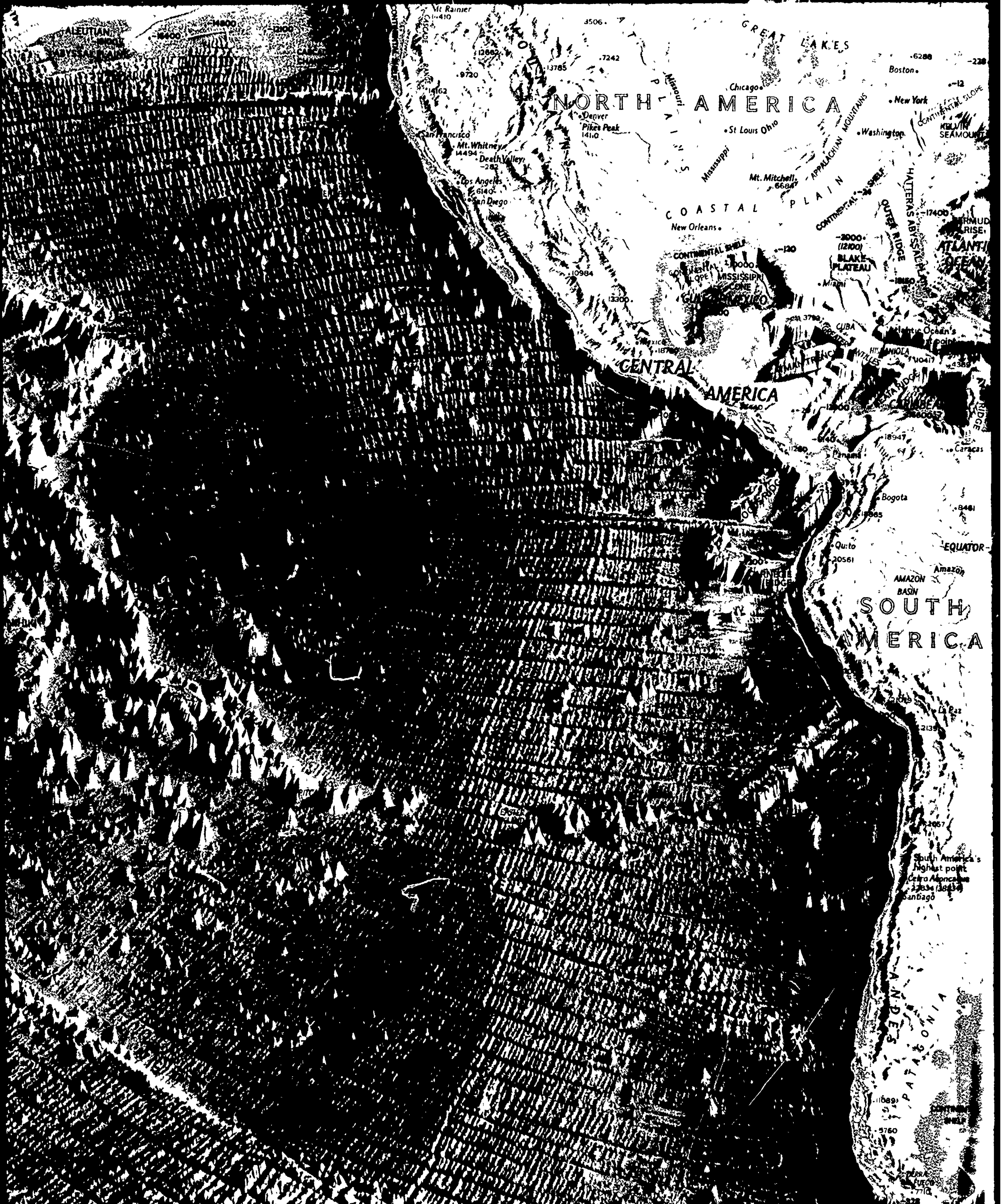

ALEUTIAN
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San Diego
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OUTER RIDGE
New Orleans
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BLAKE PLATEAU
ATLANTIC OCEAN
MISSISSIPPI CONE
Miami
CUBA
HISPANIOLA
CENTRAL AMERICA
Caracas
Panama
Bogota
EQUATOR
Quito
20561
Amazon
AMAZON BASIN
SOUTH AMERICA
La Paz
South America's highest point
Santiago
ANDES
PATAGONIA

6

To determine the cost of development drilling, one needs to know the number of wells required to provide the necessary amount of energy. Productivity will vary from well to well, and cannot be predicted before drilling and testing. However, in a successful development, it is likely that the average productivity of a well connected to the steam gathering system will be 3 megawatts (electrical equivalent), and that some fraction, F, of the wells drilled will not produce enough steam to be worth connecting to the system. Moreover, it will be necessary to provide at least one steam producing well on standby, to replace production from one of the other wells connected to the steam gathering system in case it collapses, or requires cleaning out. The average cost, C, of a steam producing well with its associated gathering lines will vary from \$350,000 to \$1,000,000, depending on drilling problems, depth, and remoteness of the site. The cost of production drilling to provide steam for an electrical generating capacity, P, will be

$$\text{Cost} = N_F \cdot E + \frac{P}{3} \cdot \frac{C}{1-F}$$

Assuming that P is to be 30 megawatts, N_F is 2 (prospects are chosen so that half prove to be developable), E is \$1,000,000, C is \$700,000, and F is 30 percent, the cost of exploration and drilling will be:

$$\text{Cost} = 2 \times \$1{,}000{,}000 + \frac{30}{3} \cdot \frac{\$700{,}000}{1-.3} = \$12 \text{ million}$$

or \$400 per kilowatt of electrical producing capacity.

3. Generating Capacity. Once production wells have been drilled and tested, so that the properties of the steam are known, the design of the generator can be specified. At the present time, all geothermal plants make use of steam from the well head to feed to the turbines. This means that any water or particulate matter produced with the steam must be separated, and that any undesirable gases in the steam (carbon dioxide, sulfur dioxide) will pass through the turbine and be lost to the atmosphere. Much of the energy of the steam is lost in driving it through the steam collection system, so that steam with an original pressure of 200-300 psi at a temperature of 200-250°C in the reservoir arrives at the turbine with a pressure of 50-120 psi, and temperatures of 120 to 180°C. Many problems would be avoided, and more efficient conversion of heat energy might be obtained if the heat from the geothermal fluid at the well head were exchanged to a lower boiling point fluid (isobutane, freon) in a closed system, with the gaseous second-stage fluid being used to drive a turbine. Such systems are under development only, so no prices are available for a binary fluid driven turbine. Steam turbines are conventional, and are supplied at current costs ranging from \$170,000

freon) in a closed system, with the gaseous second-stage fluid being used to drive a turbine. Such systems are under development only, so no prices are available for a binary fluid driven turbine. Steam turbines are conventional, and are supplied at current costs ranging from $170,000 to $225,000 per megawatt capacity. The combined capital costs of exploration, drilling, and generating at a fairly remote site are thus approximately $600 per kilowatt.

In a normal plant, the cost of fuel used in making steam is a large part of the price of the electricity produced. Coal will cost 3 to 5 mills (1 mill = .001$) while oil will cost 1.1 to 2.4 mills per kilowatt hour of electricity generated. Maintenance costs for a geothermal system are much lower, with experience showing that a cost of 0.5 mills per kilowatt hour is appropriate.

Geothermal energy is not readily transportable, and so must be used at the site where it occurs, as in space heating applications, or converted to a transportable form, such as electricity. It appears to us that the U.S. Navy has a number of special requirements that make the use of geothermal energy attractive under special conditions. One is the use of geothermal energy to meet base requirements, particularly for space heating, at remote bases which might by good fortune be located near a geothermal system. The other would be the use of geothermal energy to generate synthetic, high-energy fuels for high performance aircraft and missiles which may be used by the Navy by the end of this century.

The use of geothermal energy for space heating is particularly attractive in the case of bases sited on volcanic islands in harsh climates, such as Adak, Alaska. If steam or hot water from a geothermal well can be used directly to heat structures, the inefficiencies involved in conversion of heat to electricity will be avoided. At present, geothermal fluids can be piped to distances of ten miles or so, with no more than 10 percent energy loss. It is reasonable that about twice as much energy can be utilized from hot waters or steam piped from geothermal wells to a heating system as could be utilized in a system where electricity was generated and then converted back to heat. With twice the utilization, the cost per unit of heat for the ultimate user would be halved.

If geothermal energy is available at remote bases either for space heating, or for generating electricity, the advantages that could be realized are such that the Navy might wish to take advantage of them even if the cost were far higher than outlined above. At present, the energy requirements of remote bases are supplied largely by fuel oil. The unit size of a base is normally small enough that the use of a nuclear reactor is not practical. Supplying energy from geothermal sources would remove

such bases from dependence on supply ships. The need for such supply ships could conceivably strain naval capabilities during times of international crisis, so that the availability of a local, reliable energy source at a remote base can be equated to adding ships to the operational Navy forces.

In the longer range, the use of geothermal energy to synthesize high energy fuels may be of even more benefit. One such fuel that is under consideration is hydrogen. At present, hydrogen is being considered as an attractive fuel for use in high performance aircraft and in rocket-propelled missiles. Hydrogen contains about ten times the energy per unit weight as the best available liquid hydrocarbons, which would make it an ideal fuel for weight-limited vehicles. Unfortunately, even when liquified, it takes up three times the volume of conventional fuels. Moreover, liquid hydrogen is difficult to handle with present technology, and has an adverse effect on the mechanical properties of metals which it contacts. If these problems in handling hydrogen are solved, it would be a fuel of great utility in Navy operations.

Hydrogen is manufactured from water primarily by hydrolysis, and some is produced by chemical reactions at high temperatures. Any energy source might be used to provide the electricity for hydrolysis, but from the viewpoint of overall efficiency, the least transportable forms of energy, such as geothermal energy, are the ones that might be used most effectively in manufacturing hydrogen. Because of the abundance of volcanoes around the Pacific Ocean, particularly in areas such as the Aleutians where there is no local population to take advantage of the energy, it is likely that there are large resources of geothermal energy that cannot otherwise be used.

To provide a basis for determining the geothermal energy potential of the Pacific Basin region and for definition of particular areas that appear to warrant exploration, we have conducted a reconnaissance study, mainly from the literature, which is the subject of this report. Terrain seeming prospective for geothermal energy, amounting to a few percent of the vast Pacific region, is delineated. In addition, two particular areas, Lualualei, Oahu, Hawaii and Adak, Alaska, appeared especially attractive for several reasons and these areas were further evaluated geophysically in the field. The report on this work comprises Appendices A and B in a separate companion volume. Our total effort is designed to provide a springboard for development of geothermal energy sources for Navy utilization in the Pacific region.

We extend our thanks to Mr. George Sanders and Mrs. Diane Westfahl for assisting with data compilation, to Mrs. Fran Butler and Miss Sandi

springboard for development of geothermal energy sources for Navy utilization in the Pacific region.

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II. REVIEW OF EXPLORATION METHODS FOR GEOTHERMAL ENERGY

As pointed out by Combs and Muffler (1973), in geothermal energy exploration the commodity being sought is heat. The heat that is produced is contained in and transported by, hot water and/or steam. An exploration effort for commercial energy sources consists of coordinated geological, geophysical, and geochemical investigations that must be tailored to specific and usually unique geologic-hydrologic conditions prevailing in a given area of interest. An optimal exploration program is composed of three major phases: 1) reconnaissance--wherein from regional studies specific areas of promise are identified, 2) delineation--wherein these areas are assessed and compared in detail for geothermal potential, and 3) evaluation--wherein exploratory deep drilling to the reservoir is undertaken and numerous physical and chemical aspects of the rocks and fluids are determined.

This section describes in brief some of the main approaches utilized in a modern geothermal exploration program for hot water-steam systems. References with much greater coverage of the subject include Healy (1970) and McNitt (1973) for geology, Banwell (1970) for geophysics, White (1970) for geochemistry, and Combs and Muffler (1973) and Grose (1971) for exploration in general.

Geological Methods

The geologic approach is directed to discovery of areas with surface thermal manifestations (most commonly thermal springs), tensional tectonic features, volcanic activity, favorably permeable rocks with insulating impermeable "cap rocks," and favorable hydrologic recharge potential.

Thermal spring areas of interest should be mapped at a scale appropriate to ascertain geologic-hydrologic framework and controls and possible relationships of the systems. Other basic data needed are temperature, flow volume, associated deposits, chemical characteristics (see Geochemistry section), changes in location, behavior, etc. through time.

The structural setting should be thoroughly understood from the standpoint of: 1) old (pre-Pliocene), inactive features that determine the three-dimensional lithologic geometry and occurrence of tectonically induced permeable reservoir zones and 2) young (Pliocene-Quaternary) and active tensional faults and rifts that indicate areas of thermal fluid

and possibly magma movements. The Late Pliocene-Quaternary tectonic history of a geothermal area should be related to volcanic and hydrologic regime and to modern deformation (seismicity) to gain information on evolution and location of modern geothermal activity. Stress-strain analysis of neotectonic features will point up where the crust is rifting, uplifting, downdropping, opening, or simply fracturing. Areas of rifting appear most favorable from the tectonic viewpoint.

While not all geothermal areas are within several tens of miles of Quaternary volcanic activity, most of them are. In the island-arc environment the intermediate and acidic volcanic rocks are more closely associated genetically and spatially with geothermal systems than are the basaltic rocks. In the simatic Pacific Ocean basin environment where basalt prevails, geothermal cells are likely to persist astride and above central vents on volcanic islands within a periphery of late alkalic differentiates. Large equidimensional igneous masses cool more slowly and transmit more heat to surrounding rocks than do slender pipe or thin sheet intrusions. Generally, the younger the intrusion, the greater the residual heat content. Volcanic vent, dike, and sill geometry should be ascertained with respect to stratigraphic and structural features on an areal or regional scale. Alteration and epithermal mineralization zones may represent ancestral hot spring systems that may relate in one or more ways to occurrence of modern systems. Exploration in neovolcanic terrain seldom can draw upon well or subsurface geologic information and therefore it becomes necessary to search in the field in greatest detail for volcanic, tectonic, and hydrologic features that can be wisely used to determine and guide geophysical and geochemical investigations, and, in concert with these, can be used to construct reasonably correct three dimensional models of geothermal systems prior to deep drilling.

Since heat extraction and reservoir life depend heavily on hydrologic conditions, the hydrogeology of geothermal areas must be fully understood (Healy, 1974). Volume of stored water, areas and rate of recharge, capacity for horizontal flow, etc. must be determined. Chemistry of non-thermal and thermal waters must be assessed and related to locations of hydrothermal systems. All well data and natural recharge and discharge areas should be integrated into a hydrologic framework that will assist in determining the source of the heat and the nature of the reservoir, if indeed a reservoir, in the conventional sense, really exists.

In short, the geologic investigations should emphasize the tectonic, volcanic, and hydrologic features produced by processes active from Pliocene to the present time. Geophysical and geochemical investigations should be guided by, and interpreted on the basis of, the geology.

cene to the present time. Geophysical and geochemical investigations should be guided by, and interpreted on the basis of, the geology.

Geophysical Methods

A variety of geophysical methods is being used in exploration for geothermal reservoirs, with some intended to detect the effects of heating directly, and others intended to provide indirect information about geologic environments that are favorable for the occurrence of geothermal systems.

The most direct approach to exploration is the detection of high heat flow. This may be done in a number of ways, including infra-red imaging, measurement of temperature in shallow holes, and measurement of heat flow, usually in deeper holes. In infra-red imaging, the temperature of the surface of the earth is measured with a scanning device, flown aboard an aircraft or satellite. Present systems do not have adequate sensitivity to detect temperature differences caused by high heat flows (any heat flow more than five times normal, or 7.5 microcalories per square centimeter per second), but they can locate seeps of warm water from the subsurface, and these then can be studied on the ground. Normal atmospheric variations in temperature mask the contribution to surface temperatures by high heat flow, but to a large extent, this problem can be avoided by making temperature measurements at shallow depths beneath the surface. A simple approach is to punch holes to one-meter depth with a slide-hammer, and make temperature measurements at that depth. If the water table is nearly at the surface, local changes of temperature of 1 or 2°C can be indicative of a geothermal system at depth. However, the most reliable thermal data are obtained by drilling holes to 100 or 200 meters depth beneath the water table and determining the heat flux. This requires that both the temperature in the hole and the thermal conductivity of the rock be determined. In order for results to be reliable, the hole must be drilled in rocks in which no convection or water permeation is taking place, and where the thermal gradient is vertical. This means that the hole must be drilled in an area with low surface relief, and lateral homogeneity of rock types. Such determinations of heat flow are expensive.

The most widely used method of geothermal prospecting is the measurement of electrical conductivity. The use of the method is based on the fact that raising the temperature of a water laden rock from 20°C to 300°C will increase the electrical conductivity by a factor of seven. Thus, detection of electrical conductivity anomalies provides an indirect means of locating rocks with higher than normal temperatures.

Many techniques are used in electrical prospecting for geothermal systems. The principal requirement for a technique to be effective is that it provides adequate capability for current to penetrate 2 to 3 kilometers in highly conductive rock. Geothermal systems generally have electrical resistivities below 10 ohm-meters, and often below 3 ohm-meters. Among the techniques that are being used are the dipole mapping method, the time-domain electromagnetic method, and the Schlumberger sounding method.

The dipole mapping method is a reconnaisance method. It proceeds very rapidly in field application, but is useful only to obtain an approximate idea of the location of areas with low resistivity. In application, a current field is established in the earth by driving a large amount of current, often several hundred amperes, through a grounded wire of several kilometers length. The electric field caused by this current is mapped out to distances of ten or 15 kilometers from the bipole source. Areas of low resistivity are identified by low values of electric field intensity.

In time-domain electromagnetic sounding (TDEM), an electromagnetic field is generated by passing a step of current through a short length of grounded wire (the length may be a kilometer or less). The transient magnetic field accompanying this step in current is detected at a sounding site by using a magnetometer to record the vertical component of magnetic induction. The transient decay of the magnetic induction is interpreted in terms of the electrical resistivity profile beneath the receiver site.

Schlumberger sounding is a conventional technique for determining the electrical resistivity profile in the earth which has been used for over half a century. Four electrode contacts are used, two to drive current into the earth, and two to measure the electric field caused by the current. In sounding, the distances between the electrodes are increased sequentially as measurements are made. It is then presumed that measurements made with larger distances between the electrodes reflect the resistivity of greater depths in the earth.

In addition to electrical resistivity measurements, seismicity studies have found wide application in geothermal exploration. It has been observed in all known geothermal fields that frequent low-level seismicity occurs. The reason is not clear, but it may be that thermal stresses lead to rock breakage, or that hot fluids in the reservoir enter fractures under pressure, permitting the rock to slip. Because the seismicity is low level, it is necessary to use a very local array of seismic stations to study it, with stations separated by distances of

reason is not clear, but it may be that thermal stresses lead to rock breakage, or that hot fluids in the reservoir enter fractures under pressure, permitting the rock to slip. Because the seismicity is low level, it is necessary to use a very local array of seismic stations to study it, with stations separated by distances of only 5 or 10 kilometers. In carrying out a survey, an array of 7 or 8 stations is sited in the vicinity of a suspected geothermal system, and operated for 10 to 30 days, or long enough to establish the recurrence rate for earthquakes of magnitude 0 and larger. With a tight grid of stations epicenters can be located with a precision of 1/2 kilometers or so, with swarms or clusters of earthquakes identifying localities which are potentially geothermal reservoirs.

Information from local earthquakes can often be used to infer the characteristics of a geothermal reservoir. By comparing the arrival times for compressional and shear waves, a value for Poisson's ratio for the rocks along the travel path can be estimated. Laboratory studies have shown that Poisson's ratio increases by about 0.1 when an otherwise competent rock is microfractured by heating. A reservoir in which such fracturing has taken place, and where permeability for the flow of fluids exists, can often be identified from such data.

Still another use of local seismicity studies is in the detection of shear-wave shadows above magma chambers. Shear waves are not readily transmitted through a volume of hot, or partially molten rock. Seismic waves received from distant earthquakes can be used to detect shadow zones where shear waves do not reach the receiving array.

Finally, gravity and magnetic surveys may be used in the conventional manner to map the configuration of intrusives. If igneous rock has been intruded into high-porosity rocks, a local gravity high will be formed. If the heat source is molten rock in the crust, often, a gravity low will be observed. When rocks are heated to temperatures above 300-350°C, they become non-magnetic, and this phenomenon can be recognized on a magnetic survey.

Geochemical Methods

Geochemical surveying in geothermal energy exploration programs can provide information on the type of system (hot water or vapour-dominated), the base temperature of the reservoir, and the source, age, and distribution of waters. Waters and gases from hot spring areas should be very carefully sampled and analyzed. Spring water of low chloride content (less than 20 ppm), near-boiling temperature, and low discharge suggest presence of a vapour-dominated system. Silica content and sodium/potassium/calcium ratios can provide estimates of the minimum subsurface temperature (Fournier and Truesdell, 1973). Hydrogen and oxygen isotopic composition may indicate origin of the thermal waters, and under ideal

conditions tritium and C^{14} may be useful in determining minimum age of recharging water. Geochemical sampling of springs and wells provide insight into the composition of aquifer rocks, volcanic contributions, fluid movements, etc. and enable prediction of production problems such as corrosion, precipitation, and effluent disposal or chemical extraction.

III. SUMMARY OF THERMAL FEATURES IN THE PACIFIC REGION

An initial and rank reconnaissance assessment of a region for possible occurrence of commercial geothermal energy sources (hot water and steam) is concerned with tectonic framework, Pliocene to modern (active) volcanism, heat flow values and patterns, and thermal spring phenomena. These data are recorded for the Pacific region on Plates II to XVII at scale of 1:20 million, and explained in Appendix C.

Tectonic Features

Basically the three tectonic features that seem to exert most control over the regional localization of shallow positive thermal anomalies are the rift or spreading zones (including back arc spreading areas and some small ocean basins), the volcanotectonic arc zones, and to a minor and local extent the lateral or transform fault zones. These tectonic features usually form lithospheric plate boundaries. Therefore, from a regional tectonic viewpoint, the prospects of occurrence of geothermal systems decrease with distance away from the influence of these tectonic zones.

Tensional tectonic deformation is essential in the shallow crustal levels, if not the deep as well, to permit intrusion of magma which is mostly responsible for transporting large and local quantities of heat to the upper levels in the crust. The oceanic rifts or spreading zones, such as the East Pacific Rise, and interarc and backarc spreading basins, such as the Lau Basin and Sea of Japan respectively, are primary extensional areas. The volcanic island arcs and continental cordillera (Andean type margin) are built up in basically the compressional tectonic environment of colliding plates. However, along the volcanoplutonic axis of the leading edge of the overriding plate, secondary shallow tension results from upwelling magma and geanticlinal arching. Examples include the Java, Kurile, Aleutian, and Andean areas. Transcurrent or transform fault zones display a component of pull-apart or tension in associated normal or diagonal-slip enechelon fault patterns, such as along the southeast end of the San Andreas fault system in California and Sonora and the northeast end of the Alpine fault in New Zealand.

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In each of the above regional tensional tectonic environments, contemporaneous volcanic activity is evident and undoubtedly genetically related to the tectonic activity. The interdependent processes of tectonic opening and magma upwelling create the environment most favorable for the development of commercial geothermal systems.

In contrast to tensional areas of high heat, there are compressional areas of low heat that are generally unfavorable areas for occurrence of geothermal systems. These areas are oceanic trenches and the arc-trench gap (including forearc basin and forearc if present) where the relatively cold oceanic lithospheric plate is subducting (Oxburgh and Turcotte, 1970). Examples of such terrane are Kodiak Island, Timor Island, and the Andaman-Nicobar-Mentawai island forearc.

Collision (orogenic) tectonic processes clearly control the loci of the nearly all of the historically active volcanoes in the Circum-Pacific "Ring of Fire." Nearly all are astride an oceanic trench and above a subduction zone. Primary extensional (taphrogenic) tectonic processes seem to have localized active volcanism in the Basin and Range Province, USA, and in southeastern Papua-New Guinea. Lateral faulting (lineagenic) tectonic processes may exert major control on active volcanism in northeastern Taiwan and on nearby ocean floor, and on North Island of New Zealand.

While most of the volcanic areas can be reasonably related to a Late Cenozoic tectonic regime, it seems that the tectonic setting and the nature and degree of control over the active volcanic belt of northeastern Celebes-Kepulauan Sangihe and of Halmahera are particularly difficult to understand insofar as regional and Late Cenozoic evolutionary relationships are concerned. In this region the Indonesian-Hymalayan-Mediterranean system joins the Circum-Pacific system. Within that large portion of the Pacific Ocean basin that is floored by basaltic rocks outside the andesite line, structural control of the known active volcanic centers and trends is not clearly apparent and hence is little understood. The extensional tectonic environment of the East Pacific and associated rises probably produces submarine volcanic effusives at frequent intervals, although no historic volcanism has been reported on these spreading zones. Certainly the petrology and tectonics of Intra-Pacific volcanism is markedly different from that of most areas of Circum-Pacific volcanism. However, both bring heat to the surface and in that respect both are extremely important to geothermal resource development.

Regions of greater-than-average heat flow (>2.0 HFU) in the Pacific basin appear to correlate with regions undergoing rifting and spreading. The backarc area or small ocean basin province (Matsuda and Uyeda, 1971)

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exemplified by the Okhotsk Sea, the Sea of Japan, the Okinawa trough in the East China Sea, and probably the Shikoku Basin, the Parece Vela Basin, and the Sulu Basin, characteristically reveals high heat flow. The oceanic spreading zones - East Pacific Rise, Galapagos Rise, Galapagos Rift, and the Gorda and Juan de Fuca rises - also reveal high heat flow values. Other regions not clearly defined tectonically with supernormal heat flux include the Fiji Plateau, the Panama Basin, and a diffuse region at the "north end" of the East Pacific Rise embracing the Cedros trough and the Mathematicians Seamounts.

Tectonic control of thermal spring phenomena is evident on a regional and local scale, although most of the springs, particularly the hotter springs are obviously spatially and temporally associated with the occurrence of active volcanism. Hot spring clusters, without associated active volcanism, that occur in the volcanotectonic arc environment include areas in Colombia, Ecuador, Peru, Bolivia, Argentina, Luzon, southwestern Honshu, and central Kamchatka. Thermal spring areas without active volcanism in the rifting environment include the Basin and Range Province, Durango area in Mexico, Fiji Islands, and possibly Central Alaska and the interior of the Canadian Cordillera. Regional lateral-fault control of hot springs in inactive volcanic areas is evident in the South Island of New Zealand, in eastern Taiwan, and along parts of the San Andreas fault system of California.

Volcanic Features

Unquestionably, the strongest and most direct evidence for the occurrence of abnormally hot rocks at shallow depths is active volcanism. In order for an area to be promising for geothermal energy development from high-temperature reservoirs, the presence of Pliocene and Quaternary volcanic activity (less than 5 million years old) is the strongest single bit of evidence for hot water and/or steam systems at acceptable depth. Although the accompanying maps show only historically active volcanism, much more area would be included if all volcanic centers and rocks of Pliocene and Quaternary age were shown. Probably most of the gaps around the Pacific Ocean basin would be filled in, and a 200 to 300 mile-wide band of Pliocene-Quaternary volcanic ocean floor would be shown on the crest of the East Pacific Rise, Chile Ridge, Galapagos Rift, and Gorda-Juan de Fuca rises (Pitman and others, 1974).

The Pacific region embraces two basically different kinds of volcanism. By far the most voluminous eruptions consist of andesite with basalt and more acidic differentiates making up island arc and cordillera mountains that rim the Pacific Ocean within the andesite line. Tholeiitic basalt flows and equivalents and volumetrically minor alkalic differen-

ism. By far the most voluminous eruptions consist of andesite with basalt and more acidic differentiates making up island arc and cordillera mountains that rim the Pacific Ocean within the andesite line. Tholeiitic basalt flows and equivalents and volumetrically minor alkalic differentiates erupt from the simatic Pacific floor and spread out or locally pile up into huge basalt shields such as Hawaii, Galapagos, and the thousands of seamounts. Both kinds of volcanism are important to geothermal assessment.

From a petrologic point of view, there are many reasons for believing that geothermal systems are generated more abundantly in association with intermediate and acidic volcanic rocks than with the basaltic rocks. The vast majority of Circum-Pacific volcanoes are andesite, but most are accompanied by dacitic and rhyolitic eruptions. On the basis of variously compiled data in the International Catalogue (International Volcanological Association 1951-66), the most extensive occurrence of active volcanism in the Circum-Pacific belt more acidic than andesite is in the Ecuador-Colombia belt of active volcanoes where dacite is commonly reported.

The simatic Pacific Basin harbors several areas of active volcanism: Hawaii, Galapagos, Samoa, and several smaller areas (see below). The rocks are varieties of basalt with small volumes of trachytic and intermediate differentiates. The Pliocene-Quaternary volcanic record in the Pacific Basin is extensive and widely manifest by probably hundreds of seamounts and many deeply eroded shield volcanoes, some of which are believed to still be hot. It is generalized that oceanic volcanic products are basalt with no significant acidic contributions, but Bonatti and Arrhenius (1970) present evidence of widespread occurrence of acidic igneous rocks in the Southeast Pacific Ocean.

The occurrence of arc and rift intrusive and eruptive activity is controlled to a large degree by tensional tectonic levels in the crust as discussed previously. However, the areas of reported active volcanism in the simatic Pacific are not believed to occur over spreading centers. The two best known areas - Hawaii and Galapagos - are hypothesized to represent the ground surface penetration of mantle thermal plumes (Morgan, 1971; Wilson, 1963), which seem to bear an obscure relationship, if any, to tectonic arc or rift zones.

Primary rift volcanism is accompanied by regionally high heat flow as demonstrated by northern parts of the East Pacific Rise system, the Basin and Range Province, and the Fiji Plateau. Arc volcanism is not necessarily associated with regional high heat flow relates directly and locally to individual volcanoes in the arc. There is a tendency for regionally high heat flow to occur in the backarc basin (concave side of island arcs) or small ocean basin such as the Sea of Japan,

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but the backarc basinal area of the Aleutian volcanic arc, Bering Sea, shows no tendency to high heat flow.

No active volcanic areas apparently are completely free of thermal springs. Active volcanic areas appear to include the great majority of reported thermal spring phenomena. In some areas of intensive volcanism but of abnormally great permeability and heavy rainfall, such as Hawaii and the Galapagos, cold surficial groundwater sweep masks and diverts flow of underlying hot waters thereby greatly reducing the number of surface thermal manifestations in the area.

Heat Flow Values

Heat flow values gathered to date are generally rather widely and unevenly scattered through the Pacific Basin. Many local and regional environmental, structural, and age factors may affect heat flow and they introduce difficulties in obtaining reliable values for conductive heat flow (Langseth and Von Herzen, 1970). Where numerous closely spaced values have been obtained, for example across the Galapagos rift (Williams and others, 1974) where they rise to 30 HFU, hydrothermal convective heat flow dominates. The significance of a single anomalously high value in an otherwise low heat flow region is usually unknown. Several measurements considered together have more meaningful value.

Heat flow may be locally high but also very irregular in rift areas and in volcanic .eas. It is characteristically low on open-ocean sides (convex side) of trenches, in trenches (though data are very sparse here), and in the arc-trench gap zone. The relationship between heat flow and tectonism and volcanism has been briefly discussed previously.

There is certainly a direct correlation between high heat flow and thermal springs on land, but the patterns are essentially unknown in the submarine environment of the Pacific Basin.

In geothermal exploration heat flow measurements are a useful tool in regional thermal comparisons and assessments, but their greatest value usually lies in evaluating many, but not all, areas believed to contain the individual geothermal cell of a few miles dimension.

Thermal Springs

Wherever thermal springs are found, they indicate anomalously elevated rock temperature at shallow depth, or anomalously deep groundwater circulation in areas of normal thermal gradient, or both conditions. In the Pacific region the vast majority of thermal springs occur in active volcanic areas and almost all occur where Pliocene-Quaternary volcanism has occurred. Thermal springs are an excellent clue to local and regional areas with high probability of containing potentially commercial geo-

the Pacific region the vast majority of thermal springs occur in active volcanic areas and almost all occur where Pliocene-Quaternary volcanism has occurred. Thermal springs are an excellent clue to local and regional areas with high probability of containing potentially commercial geothermal systems. Their relation to tectonics, volcanism, and heat flow has been summarized.

IV. THERMOGEOLOGIC SUMMARY OF SPECIFIC AREAS

Adak Alaska

Adak Island is located toward the western end of the active volcanic portion of the Aleutian island arc. In many respects the island is similar to most of the Aleutian Islands with Quaternary volcanoes, although no historic volcanic activity occurs there.

Two Quaternary basaltic and andesitic volcanoes are of particular interest for geothermal development since they are situated several miles from the Adak Naval Base. Mt. Adagdak is a basaltic shield volcano with composite cones and two domes. Younger olivine basalts are radiometrically dated at 0.16 my and 0.23 my (Marlow and others, 1973). The northeastern quadrant of the mountain is crisscrossed by several recent fault scarps (Coats, 1956). Hot springs occur low on the west slope. Mt. Moffet is larger than Mt. Adagdak, is a more homogeneous basaltic shield accumulation, and is lacking in modern fault scarps. To the west-southwest of Adak, Kanaga volcano has erupted in recent years.

A microseismicity survey was carried out by the Colorado School of Mines on the west flank of Mt. Adagdak. A report of this effort is presented in Appendix A of this report.

The Adak area appears favorable for occurrence of shallow volcanic heat sources that may be tapped for geothermal energy utilization.

Fiji Plateau

The Fiji Plateau area, about 500,000 square miles, ranks as one of the most complexly evolving tectonic and volcanic segments of the entire Circum-Pacific belt. Also, it appears to be one of the largest areas of high heat flow, relatively equidimensional as contrasted with linear "mid-oceanic rifts," known to date in oceanic or quasi-oceanic regions of the world. Various aspects of the geology of Fiji, mainly the two islands Viti Levu and Vanua Levu, are treated in articles by Coulson (1971), Gill (1970), and Rodda (1967). The geologic map of Fiji is authored by Phillips (1965), and regional tectonics articles include Green and Cullen (1973), Chase (1971), and Dickinson (1967).

The bulk of the rocks on Fiji's main islands is andesite and basalt of Miocene-Pliocene age, resting on an older series of compressed and moderately metamorphosed volcanics containing gabbroic stocks which date back to the Eocene. In the Pleistocene, basaltic outpourings increased forming shield- and plateau-layered accumulations in association with tensional strain and local spreading in the region.

Tectonically, the Fiji Plateau appears to reflect interference of at least 6 small blocks (microplates?) between the Pacific and Australian plates (Chase, 1971). Island arcs border the Plateau on east and west and transform and possibly spreading linears occur on the north and south.

High heat flow is represented by many values over 3.00 HFU (Plate XII) on the Plateau, whereas in the fault systems and ocean floor to the north and east many values are below 1.00 HFU. The regionally high heat flow and Quaternary basaltic volcanism are evidence for spreading or tensional tectonics (Macdonald and others, 1973; Sclater and Menard, 1967), all of which are basically favorable geological conditions for a large geothermal energy potential.

Hot springs occur widely in the Fiji Islands (Plate XIII). Many of them (37 in number) are described and evaluated by Healy (1960) who reported on the geothermal resources of Fiji. Temperatures are mostly less than 60°C, but at Savusavu on Vanua Levu the springs are boiling. Meteoric and oceanic water circulating along faults to depths greater than 2000 feet are apparently heated by shallow hot rocks and underlying magma pockets. The geothermal regime in the Fiji Islands appears promising for development of energy.

Galapagos Islands

The Galapagos Island group is composed of fifteen main islands and numerous islets covering an area of 2870 square miles elongate northwest-southeast for 230 miles. Eight of the islands have active volcanoes with records of historic eruptive and/or fumarolic activity. Recent references to the geology of the Islands include Delaney and others (1973), Nordlie (1973), and McBirney (1969).

There are 20 principal volcanoes and about 2000 parasitic craters, all recent and relatively freshly preserved. All eruptive centers are basically similar; nearly all the rock on the Islands is basalt; and volcanism seems to reflect essentially one cycle. Solfataras occur only within calderas and thermal springs are rare. No coral reefs occur on the Galapagos Islands, since water temperatures frequently dip below 71°F, the temperature necessary for viable coral growth. Evidence suggests uplift rather than subsidence in the Islands (Chubb, 1933), and faulting appears

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The Galapagos Islands occur on the west end of the 600-mile-long Carnegie Ridge and 100 to 200 miles south of the Galapagos Rift (Plate VI). A major north-south transform fault which cuts the Galapagos Rift projects southward into the area of the Islands. The nature of the Carnegie Ridge is little known, but it has been suggested by Herron (1972) that it may reflect eastward movement of the Nazca plate over a fixed mantle hotspot (Morgan, 1971). Within the Galapagos Island group the youngest volcanism occurs to the west and the Islands themselves are located at the west end of the Carnegie Ridge.

The geothermal energy potential of the Galapagos Islands should be excellent. The geothermal systems there would be analogous to those believed to occur on Hawaii since the local and regional volcanic framework appears similar to the Hawaiian setting.

Guam

The Island of Guam is the southernmost island in the Mariana volcanic arc. It has an area of 212 square miles and is underlain by Late Tertiary reef limestone in the north, Eocene volcanics in the central part, and Miocene volcanics in the south. These three areas have been normal block faulted and are separated by major transverse faults (Tracey and others, 1964). Evidentally, an Eocene volcano formed about 12 miles west of the central part of Guam and a Miocene volcano formed about 6 miles west of the southern part of Guam. Following explosive eruptions, both volcanoes underwent caldera collapse which extended a zone of normal block faulting as far east as the west margin of the present Island of Guam. Post-collapse eruptions built up two submarine cones 12 and 20 miles west of the Island. Their ages are uncertain, but the southern cone is probably post-Miocene.

Guam, as well as Saipan and Tinian, are located several miles east of the southern projection of the historically active line of volcanoes comprising the Mariana arc. The nearest reported active volcanism to Guam was about 100 miles north - a submarine eruption south of Saipan (Plate XV).

The tectonic setting of Guam and the Marianas is the subject of many recent papers, two of which are Bracey and Ogden (1972) and Karig (1971). Guam is situated above an active west-dipping subduction zone with frequent intermediate depth earthquakes and a significant regional right lateral component of overthrusting associated with the southwesterly bend in

the Mariana arc.

Presence of volcanogenic normal faulting and Late Tertiary volcanism astride the Island make Guam a moderately promising area for persistence of volcanic heat that may be utilized for the generation of electricity.

Hawaiian Archipelago

The Hawaiian Archipelago extends for about 2000 miles from the island of Hawaii on the southeast to beyond Midway Island to the bend with the Emperor seamount chain on the northwest. The eight large Hawaiian Islands, spanning a distance of 400 miles at the southeast end of the Archipelago, represent the tops of probably the largest volcanic piles on earth at the present time. Smaller islands to the northwest represent older, eroded, sunken reef-capped volcanoes. Numerous articles have been written on many aspects of the geology of Hawaii and notable books include Macdonald and Abbott (1970) and Stearns (1966).

The rocks of the Islands are mainly pillow lavas, pyroclastics, and lava flows nearly all of basaltic composition. Volumetrically minor and eruptively later differentiates include andesite, trachyte and nephelinitic basalts. Major fractures run east-west through the Islands (notably the Molokai zone, Plate II) and local fractures trend irregularly in northwest and northeast directions (Malahoff and Woollard, 1968). Major volcanic centers on the individual islands display two or three dominant radial fractures or rifts which are loci of frequent and persistent fissure vent eruptions.

The earliest volcanic activity occurred at the northwest end of the Archipelago in the Midway vicinity (Ladd, 1970) and progressed episodically from Miocene to the present in a southeastwardly direction to the Island of Hawaii where modern eruptions are now occurring (Dalrymple and others, 1974; Jackson and others, 1972). Present rates of eruption on Hawaii at Kilauea are estimated at 0.11 km^3/yr (Swanson, 1972); this far exceeds the calculated average eruption rate for the Hawaiian Archipelago (Barger and Jackson, 1974).

Primary magma chambers are believed on the basis of xenoliths and volcanogenic seismicity to be situated in the upper mantle at about 30-40 miles in depth (Wright, 1971). Locally magma batches are believed to occur at intermediate depths and at shallow depths (1-4 miles) beneath major volcanoes, and eruptive material may be derived directly from all levels. Prevailing thought on the origin of the Hawaiian Islands seems to favor a mantle "hot spot" or thermal plume hypothesis (Dalrymple and others, 1973), but other somewhat different yet related hypotheses, such

directly from all levels. Prevailing thought on the origin of the Hawaiian Islands seems to favor a mantle "hot spot" or thermal plume hypothesis (Dalrymple and others, 1973), but other somewhat different yet related hypotheses, such as the downwelling and fractionated gravitational anchor mechanism (Shaw and Jackson, 1973) are also favored by some petrologists. Certainly, an understanding of the mantle and crustal processes that effect such large shallow heat reservoirs have fundamental bearing on the exploration for, and potential utilization of, heat energy in the earth's crust.

The problem of cooling rates of intrusions is of critical importance in exploration for geothermal energy in Hawaii. The bulk of the volcanism on Oahu is dated between 2½ and 3½ million years old, yet late phase activity occurred sporadically up to the last 30,000 years in the Honolulu Volcanic Series (Gramlich and others, 1971). On the basis of magnetic data, Furumoto (1974) concluded that the Koolau volcanic center could still be hotter than the Curie Point (±325°C). It seems entirely possible that other central intrusive masses on the eight main Hawaiian Islands (Waianae, Hualalai, Maunakea, etc.) could maintain elevated temperatures at relatively shallow levels for hundreds of thousands of years or even several millions of years.

Geological prospects for utilization of steam and the direct use of volcanic heat in Hawaii are reviewed by Macdonald (1973). A geothermal research hole was drilled at the summit of Kilauea volcano (Keller and others, 1974). A preliminary electrical resistivity and shallow temperature survey was conducted by the Colorado School of Mines at Lualualei, Oahu and is presented in Appendix B of this report. Prospects for geothermal energy development on Hawaii and the other nearby islands appear especially favorable.

Philippine Islands

The Philippine Islands comprise a complex volcano-tectonic arc system 950 miles long and 150 to 250 miles wide. A long history of plutonism, volcanism, and tectonism is recorded beginning with Paleozoic rocks and continuing through the Mesozoic and Cenozoic to the present. The geologic framework of the Philippines is discussed by Alcaraz (1947, 1972), Gervasio (1973), Gervasio and Fernandez (1967), Irving (1950), and Santos-Inigo (1966).

From the Miocene to the present, the period of geologic time of particular interest to geothermal resource studies, quartz dioritic batholiths were emplaced (Miocene) and followed by dacitic and andesitic flows, pyroclastics, and plateau basalts, the latter apparently largely restricted to Mindanao and Luzon.

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Active volcanoes in the Philippine Islands number 31 and they occur widely (Plate XV), but are markedly absent in most of Luzon. Yet in the avolcanic portion of Luzon thermal springs are abundant (Plate XVII), which suggests shallow heat sources perhaps of a volcanic origin. The island of Cebu also has numerous thermal springs but no active volcanoes.

The tectonic features of greatest importance to geothermal phenomena are Pliocene to Holocene grabens and horsts of tensional origin which occur in the central areas occupied by acidic to intermediate plutonic arcs of Miocene age and volcanic effusives of Quaternary age. Older peridotite arcs are present on both the eastern and western sides of the Islands and these are largely free of geothermal manifestations. A complex left-slip fault zone trends northwest-southeast through the Islands (Allen, 1962), but its influence, if any, on modern geothermal systems is little understood, because post Miocene displacement relative to volcanism and deformation is little known.

The following factors summarized and modified from Alcaraz (1974), pertain to the geothermal energy potential of the Philippines:

1) Potential areas occur between the peridotite arcs in the acidic plutonovolcanic arc.

2) Inactive and active volcanoes are promising areas.

3) Structural controls are volcanotectonic grabens and local tensional faults auxiliary to possible Quaternary movements along the Philippine fault zone.

4) Reservoir rocks are porous pyroclastics and fractured flows and underlying crystalline rocks.

5) Heat sources are shallow magma chambers.

6) Circulating ground water is heated by contact with hot rocks which in turn derive their heat from underlying magma.

The Philippines appear to possess a very high potential for geothermal energy. Grindley (1964) observed that 41 thermal fields appear highly favorable and that 30 more could be promising when more knowledge is acquired.

Samoan Islands

The Samoan Islands consist of three major islands, Savai'i, Upolu, and Tutuila, and Manu'a group of several small islands, altogether comprising a west-northwest volcanic trend about 200 miles long. They are located 100 miles north of the bend in the Tonga trench and entirely within the oceanic environment. The geology of the Islands is the subject of reports by Stice (1966), Lear and Wood (1959), Macdonald (1944), Stearns (1944), and Daly (1924).

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located 100 miles north of the bend in the Tonga trench and entirely within the oceanic environment. The geology of the Islands is the subject of reports by Stice (1966), Lear and Wood (1959), Macdonald (1944), Stearns (1944), and Daly (1924).

The Samoan Islands are a basaltic edifice built up over 12,000 ft thick during Pliocene and Quaternary time. Four volcanoes have been active in historic time, and numerous volcanic land forms attest to youthfulness of much activity. Late eruptive phases contain trachytic varieties of differentiates from the basalt. Extrusion linears trend west-northwest and east-northeast along fracture zones. Hot spring and fumarolic activity are rare. The volcanic regime appears to resemble that of the Galapagos and Hawaiian islands. The geothermal prospects should be excellent in Samoa.

Small Volcanic Islands

Numerous islands in the simatic portion of the Pacific Ocean have volcanic foundation rocks that are exposed above sea level (Plate I-A). Some of these islands are mountainous and composed entirely of volcanic rock; some are volcanic rock with fringing reefs; others are mainly atoll with small erosional residuals of volcanic rock protruding above sea level. Large groups of islands, such as the Marshalls, Gilberts, Tuamotos, etc. are entirely atoll with submarine volcanic rock pedestals. These are not listed.

The atoll capping a volcano reveals that extensive erosion and sinking of the volcanic edifice have occurred through millions of years since the final eruptive phase and that in all probability the remnant volcano is cold. Heat flow and thermal gradient data from Eniwetok and Bikini atolls support that inference based on geologic history (Swartz, 1958; Birch, 1956). However, many oceanic volcanoes are young; they range from eruptively active and uneroded to inactive and deeply eroded, slumped and subsided. Quantitative data on rates of cooling of magma within volcanoes are lacking, but geologic reconstruction of the life history of basaltic shield volcanic centers suggests that in some cases temperatures of several hundred degrees C may persist at shallow depth for at least two million years. Therefore, all volcanic islands on the simatic Pacific floor that still have volcanic rocks exposed above sea level and that are of Pliocene-Quaternary age should in general be considered as possible geothermal energy sources.

V. A NOTE ON POSSIBLE OCCURRENCE OF GEOPRESSURED SYSTEMS IN THE PACIFIC REGION

Thermal energy stored in pore water in sediments filling deep basins may be many times greater than that from localized hydrothermal systems. If a basin is large, deep, and filled with alternating sandstone and thick shale beds, and if it has been tectonically stable (except for subsidence) over tens of millions of years, water and heat become trapped under high pressure beneath impermeable insulating clay shale beds. The formation waters are largely connate - rather than circulating meteoric waters - produced by compaction and dehydration of the sediments. The deep (>10,000 feet) geopressured sedimentary rocks are poor conductors of heat since the thermal conductivity of water is about one-fourth that of sedimentary mineral grains. The specific heat of the trapped water is about four times that of the mineral grains. Thus, the geopressured section has retarded the natural upward flow of heat and has accumulated large amounts of heat beneath an insulating blanket of thick shale ("a natural pressure cooker").

Geothermal resources of the deep high-pressure section in the Gulf Coast area (northern Gulf of Mexico basin) of the U.S.A. have been described by Jones (1970). At depths from about 8000 to greater than 15,000 feet, abundant water may be encountered at temperatures up to 250°C and pressures up to 15,000 Psi. Relatively little is known about the economic energy potential from geopressured systems in the Gulf Coast area, because investigations are only now approaching the pilot-plant or demonstration plant stage.

Knowledge on possible occurrence of geopressured systems in the Pacific region is next to non-existent in the published record. The special geologic conditions (previously mentioned), which must evolve and be maintained in order to create a geopressured thermal resource of potentially commercial value, are not present in most areas of the Pacific region. Probably the only areas which may have a possibility of a geopressured potential are located in the Indonesian archipelago and possibly in the small ocean basin areas of the western and southwestern Pacific. Specific basins in the Timor Sea, Gulf of Thailand, South China Sea, and Java Sea may possess geopressured sections that merit study for geothermal resource development.

VI. GEOTHERMAL DEVELOPMENT AROUND THE PACIFIC

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VI. GEOTHERMAL DEVELOPMENT AROUND THE PACIFIC

Geothermal development around the Pacific has had a fifty-year history, with electrical power now being generated from geothermal steam in the United States, Mexico, El Salvador, New Zealand, Japan and Russia. Exploration and development programs are well advanced in other countries, including Nicaragua, Chile, the Philippines, and Indonesia.

Western United States

By far the most intensive development of geothermal energy is taking place along the Pacific Coast of the United States. The world's largest geothermal field (at present) is located at the Geysers, approximately 75 miles north of San Francisco. Present production is 500 megawatts, with additional capacity of 700 megawatts under construction or planned. The extent of the Geysers field has not yet been defined.

Potentially, the world's largest geothermal province, the Mexicali-Imperial valley has not yet been developed because of problems with the salinity of geothermal fluids. A number of high-grade geothermal cells have been drilled, and large-scale production of electrical power can be expected within a few years, as the technical problems related to salinity are solved. Geothermal fields have been defined by geological and geophysical studies, and by exploration and production drilling, at Heber (Chevron Oil Company), Brawley (Union Oil Company), and East Mesa (U.S. Bureau of Reclamation). Numerous other exploratory wells have penetrated into zones with geothermal temperatures, but these three locations are the ones presently under development.

One geothermal test well has been drilled at Kilauea Volcano, on the Island of Hawaii, by the Colorado School of Mines under a National Science Foundation grant. A second test well has been authorized, with funding provided by the Energy Research and Development Administration, and with the University of Hawaii serving as operator.

Mexico

The Mexicali-Imperial valley geothermal province extends into northern Mexico in the vicinity of Mexicali, and here, at Cerro Prieto, the Mexican government has operated a 75 megawatt plant since the Spring of 1973. Generators have already been ordered for the second increment of 75 megawatts, and it appears that 150 megawatts is nowhere near the capacity that could be supported by the Cerro Prieto field.

Mexico has abundant geothermal potential, and an exploration program to locate other sites is underway.

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El Salvador

A joint exploration and development program of the government of El Salvador and the United Nations has led to the definition of geothermal reservoir at Ahuachapan. The first increment of production, 30 megawatts, went into production early in 1975. Plans call for installation of a second 30 megawatt unit in the near future, with production scheduled for 1976, and a third unit of 20 megawatts is planned for 1978.

New Zealand

One of the best known geothermal developments is that at Wairakei, New Zealand. This, and other potential developments in New Zealand, are located on the Taupo Volcanic zone, a rift-like feature extending from the middle of the North Island to the northern coast. Wairakei was drilled and developed as an electrical power source in the mid 1950's. The installed capacity is 220 megawatts, though the rate of production has been maintained at 160 megawatts for most of the 20 years the plant has been operating. At Kawerau steam is used in pulp and paper industry and to generate 10 MW of electricity.

A third geothermal field along the Taupo Volcanic belt was defined and drilled in the early 1960's at Broadlands. Wells with a potential for serving a plant with 90 megawatts capacity were drilled and tested. A plant has not yet been built. As many as a dozen other prospective geothermal reservoirs have been identified by geological and geophysical studies along the Taupo Volcanic belt.

Japan

Geothermal energy has been the subject of study in Japan since 1919, and the first power was generated experimentally, on a small scale, in 1924. The first commercial production was started in 1966 with a 20 megawatt plant located at Matsukawa in northern Kyushu, followed in 1967 by a 13 megawatt plant at Otake and in 1973 by a 10 megawatt plant at Onuma. Other plants under development are a 25 megawatt unit at Onikobe in Miyagi Prefecture, and 50 megawatt plants at Hatchobara, Kyushu, and Takinoue, Akita Prefecture. Exploration is being pursued at numerous other locations.

Russia

The typically island-arc and volcanically active zone of Kamchatka has been explored by the Russians for over twenty years. Drilling began in 1957 and by 1967, a 5 megawatt power plant was in full operation. By 1980 the total installed capacity is expected to reach 25 megawatts. At Petropavlovsk, Kamchatka, a significantly successful operation of freon-

has been explored by the Russians for over twenty years. Drilling began in 1957 and by 1967, a 5 megawatt power plant was in full operation. By 1980 the total installed capacity is expected to reach 25 megawatts. At Petropavlovsk, Kamchatka, a significantly successful operation of freon-based heat exchanging from 81°C geothermal fluids has been underway since 1970.

Nicaragua

Exploration for geothermal reservoirs was undertaken with assistance from USAID in 1969, with a potential geothermal reservoir being located on the north shore of Lake Managua. A single prospect hole was drilled and this produced commercial quantities of geothermal steam. Subsequently, the government of Nicaragua contracted with the United Nations to continue further development, and development drilling is now planned.

Chile

Geothermal exploration was begun in northern Chile in 1967, under a United Nations program. Geological and geophysical studies as well as exploration drilling has defined a geothermal system at El Tatio. Plans call for the construction of a 25 megawatt plant in the near future, with power to be supplied to the Chuquicamata copper mine, located about 50 miles away.

Philippines

Union Oil Company, working with the government of the Philippines, is developing a large geothermal reservoir at Tiwi, on the Island of Luzon. Four 55 megawatt generators have been ordered to provide an installed capacity of 220 megawatts.

Indonesia

Exploration and definition of two geothermal areas on the Island of Java has been proceeding for the past several years. At one location, in the Dieng Mountains of central Java, geophysical and geological studies, partially funded by USAID, have indicated the existence of an extensive geothermal field. Also, at Kawah Kamojang in west Java, surveys carried out with Columbo Plan assistance, appear to define a large geothermal reservoir. No estimates of capacity are available.

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VIII. APPENDICES

Note: Appendices A and B are in separate volume.

APPENDIX C - EXPLANATION OF ILLUSTRATIONS, PLATES I-XVII.

GEOGRAPHIC MAP OF THE PACIFIC REGION

PLATE I

Geographic index map of the Pacific region; base for overlay Plates I-A and I-B. From National Geographic Society (1969).

INDEX TO SOME LOCALITIES MENTIONED IN TEXT

PLATE I-A

1) Numbers refer to locations of volcanic islands in the simatic Pacific basin that have volcanic foundation rocks exposed above sea level. Geologic data on the numerous islands are based on many literature sources

INDEX TO SOME LOCALITIES MENTIONED IN TEXT

PLATE I-A

1) Numbers refer to locations of volcanic islands in the simatic Pacific basin that have volcanic foundation rocks exposed above sea level. Geologic data on the numerous islands are based on many literature sources, in particular Wilson (1963a).

Number	Island	Major Rock	Age of Volcanism
	Island off West Coast of North America		
1	Revilla Gigedo	Basalt?	Active volcano
	Islands off West Coast of South America		
2	Cocos	Phonolite, Andesite	Tertiary?
3	Galapagos	Basalt	Active Volcanoes
4	San Felix, San Ambrosio	"	Active, Tertiary
5	Juan Fernandez	"	Subm. activity, Tertiary
	Islands of East Pacific Rise		
6	Sala-y-Gomez	"	Holocene, Pleistocene
7	Easter	"	Pleistocene?
	Balleny (67°S, 164°E	"	Holocene to Tertiary
	Islands of the North Pacific Ocean		
8	Hawaii	Basalt	Active
9	Maui	"	Historically Active
10	Molokai	"	Quaternary
11	Oahu	"	Quaternary, Pliocene
12	Kauai	"	Pliocene
13	Nihoa	"	Miocene
14	Necker	"	Subm. activity, Miocene
15	French Frigate Shoals	"	Miocene?
	Islands of West Equatorial Pacific Ocean		
	Caroline Islands		
16	Ponape	"	Late Tertiary?
17	Kusaie	"	" "
18	Truk	Basalt, Trachyte	Miocene?
	Rotuma Islands		
19	Rotuma	Basalt	Holocene
	Wallis Islands		
20	Uvea	"	Holocene, Pleistocene
21	Samoan Islands	"	Active, Quaternary

Islands of Central Equatorial Pacific Ocean

	Cook Islands		
22	Rarotonga	Basalt, Phonolite	Early Tertiary?
23	Mangaia	Basalt	" "
	Atiu	"	" "
24	Atiu	"	" "
	Mauki	" ?	" "
25	Aitutaki	" ?	" "
	Austral Islands		
26	Rimatara	" ?	?
27	Rurutu	" ?	Holocene, Pleistocene
28	Tubuai	" ?	?
29	Raivavae	" ?	?
30	Rapa	"	?
31	Morotiri	"	?
	Society Islands		
32	Mehitia	"	Holocene, Pleistocene
	Tahiti-Iti	Basalt, Nepheline Monzonite	Pleistocene
	Tahiti-Nui	Basalt, Basanite, Phonolite	Pleistocene?
33			
	Moorea	Basalt, Trachyte, Phonolite	Pleistocene? Pliocene?
	Tubuai	Basalt	?
	Huahine	Basalt, Trachyte, Phonolite	?
	Raiatea	"	?
34	Tahoa	Basalt, Gabbro	?
	Bora Bora	Basalt	Pleistocene? Pliocene?
	Manupiti	"	?
	Gambier Islands		
35	Mangareva	Basalt, Picrite	Tertiary?
36	Pitcairn Island	Basalt, Andesite, Trachyte	" ?
	Marquesas Islands		
	Fatu Hiva	Basalt	Quaternary? Pliocene?
	Motane	"	" ? " ?
37	Tahuata	"	" ? " ?
	Hiva Oa	Basalt, Andesite (with sulfurous spring)	" " ?
	Fatahuku	Basalt	" ? " ?
	Napou	"	" ? " ?
	Nakuku	"	" ? " ?
38	Nukuhiva	Basalt, Basanite	" ? " ?

	Hiva Oa	Basalt, Andesite (with sulfurous spring)	"		"	?
	Fatahuku	Basalt	"	?	"	?
	Napou	"	"	?	"	?
	Nakuku	"	"	?	"	?
38	Nukuhiva	Basalt, Basanite	"	?	"	?
	Mo:uiki	Basalt	"	?	"	?
	Eiao	"	"	?	"	?
	Hatutu	"	"	?	"	?

2) Localities underlined indicate where geothermal energy is currently (April, 1975) being utilized for generation of electricity.

3) Localities not underlined are briefly discussed in the text.

4) Areas outlined are those believed worthy of further study and exploration for possible geothermal energy sources.

5) Outlines of Kamchatka, Panama, and New Zealand are for matching Plates I-A and I-B over Plate I.

Notes on Plates II - XVII - These base maps covering the Pacific region are preliminary unedited copies of maps which will soon be completed and published by the U.S. Geological Survey. They will serve as Pacific Quadrant base maps for the Circum-Pacific Map Project (1974). The scale of the quadrant maps used in this report is 1:20,000,000 or about 320 miles to 1 inch or about 510 kilometers to 1 inch. The map projection is azimuthal equal area with the center for each quadrant map located near the geographic center of each quadrant. Bathymetric contour intervals are 500 and 1000 meters.

TECTONIC FEATURES IN PACIFIC REGION

PLATES II, VI, X, XIV

Symbols for tectonic features include:

- Scarps, fault zones, fracture zones based on firm evidence. U upthrown, D downthrown, → lateral movement
- Fracture zones (FZ) inferred from magnetic, bathymetric, and other evidence
- Seamount and volcanic-island chains, archipelagos, etc.
- Trenches - bathymetric axis
- Narrow troughs, grabens, synclines, small trenches
- Basin, syncline, bathymetric low
- Arch, anticline, bathymetric high
- Axis of strong negative isostatic anomaly
- Oceanic rifts or spreading zones

Sources of tectonic data listed in References Cited, include: Avias 1973, Bracey and Ogden 1972, Bullard and Mason 1963, Chase and others 1970, Circum-Pacific Map Project 1974, Coleman 1973, Dehlinger and others 1970, Geological Map of the World 1967, Gervasio 1973, Hackman 1973, Hamilton 1974, 1974a, Herron 1972, Karig 1971, 1972, Katili 1973, Ludwig and others 1973, Luyendyk and others 1973, Malahoff and Woollard 1970, Mammerick and others 1974, Menard and Chase 1970, Moore 1973, Peter and others 1970, Rea and Malfait 1974, Shor and others 1970, Stover 1973, Taylor and O'Neill 1974, Tectonic Map of the Pacific...1970, Uyeda and Miyashiro 1974, von Andel and others 1971, and Vening-Meinesz 1964.

ACTIVE VOLCANISM IN PACIFIC REGION

PLATES III, VII, XI, XV

The following symbols locate the volcanic activity on the maps and indicate the type of activity:

- ● Volcanoes with magmatic and/or phreatic eruptions
- ⊖ Volcanoes in fumarolic states; no eruptions known
- ◉ Submarine volcanic eruptions
- O Active volcanoes; nature of activity unknown
- ⊕ Solfatara fields

The following abbreviations indicate petrologic types associated with each volcano. The order is from basic (basaltic) to acidic (rhyolitic) with no order of relative abundance implied.

O Active volcanoes; nature of activity unknown

● Solfatara fields

The following abbreviations indicate petrologic types associated with each volcano. The order is from basic (basaltic) to acidic (rhyolitic) with no order of relative abundance implied.

B	basalt	o	olivine
A	andesite	p	pyroxene
T	trachyte	h	hornblende
TA	trachyandesite	l	leucite
Ba	basanite	n	nepheline
D	dacite	b	biotite
RD	rhyodacite	q	quartz
L	latite		
R	rhyolite		

The order of listing of volcanic phenomena starts with the Aleutian Islands and continues clockwise around the Pacific region ending with the Kamchatka peninsula.

Most of the data was derived from the "Catalogue of the Active Volcanoes of the World including Solfatara Fields" (International Volcanological Association, 1951-66). Other sources, listed in References Cited, include: Coats 1952, Gregg 1960, Johle and Coulter 1955, Jones 1952, Mina Kami 1956, Smithsonian Institution, Taylor 1956, Volcanological Society of Japan 1957-73, and Ward and Matumoto 1967.

NUMBER	PETROLOGY	SYMBOL	VOLCANO	LOCATION
Aleutian Islands				
1	B/A	⊖	Kiska	Kiska Is.
2	A/D/RD	⊖	Little Sitkin	Little Sitkin Is.
3	B/A/D	●	Cerberus	Semisopochnoi Is.
4	oB	●	Gareloi	Gareloi Is.
5	B/A	●	Tanaga	Tanaga Is.
6	pB/A	●	Kanaga	Kanaga Is.
7	B/A	●	Great Sitkin	Great Sitkin Is.
8		⊖	Koniuji	Koniuji Is.
9	B	⊖	Korovin	Atka Is.
10	B	O	Sarichef	Atka Is.
11		●	Seguam	Seguam Is.
12		O	Amukta	Amukta Is.
13		●	Yunaska	Yunaska Is.
14		●	Mt. Cleveland	Chuginadak Is.
15		O	Carlisle	Carlisle Is.
16		O	Kagamil	Kagamil Is.
17	B/A/RD/L	O	Vsevidof	Umnak Is.
18	oB/R	●	Okmok	Umnak Is.
19	B/hA	●	Bogoslof	Bogoslof Is.
20	B/A	O	Makushin	Unalaska Is.
21		●	Akutan	Akutan Is.
22		●	Pogromni	Unimak Is.
23		O	Fisher Caldera	Unimak Is.
24		●	Shishaldin	Unimak Is.
25		●	Isandiski	Unimak Is.
25a	oB	⊖	Frosty	Alaska Peninsula
26	B	●	Pavlof	Alaska Peninsula
27		O	Pavlof Sister	Alaska Peninsula
28		●	Veniaminof	Alaska Peninsula
29		●	Aniakchak Crater	Alaska Peninsula
30		O	Mt. Chiginagak	Alaska Peninsula
31		●	Mt. Pevlik	Alaska Peninsula
32	B/A/D/R	O		Katmai Nat'l Mon.
32a		⊖	Mt. Martin	
32b	A	●	Mt. Trident	
32c	R	⊖	Novarupta	
32d		⊖	Mt. Griggs	
32e		⊖	Kukak	
33	B/pA/D/R	●	Mt. Katmai	

32b	A	●	Mt. Trident	
32c	R	⊖	Novarupta	
32d		⊖	Mt. Griggs	
32e		⊖	Kukak	
33	B/pA/D/R	●	Mt. Katmai	
34	A/D	●	Augustine	Augustine Is.
35		●	Iliamna Volc.	Alaska Peninsula
36		●	Mt. Redoubt	Alaska Peninsula
37		●	Mt. Spurr	Alaska Peninsula

Hawaiian Islands

1	oB/pB	●	Haleakala	Maui
2	oB/pB	●	Hualalai	Hawaii
3	oB/pB	●	Maunaloa	Hawaii
4	oB/pB	●	Kilauea	Hawaii

United States

1	pA/hA	●	Mt. Baker	Washington
2	pA	●	Mt. Rainier	"
3	oB/pA	●	Mt. St. Helens	"
4	B	O	Craters of the Moon	Idaho
5	D/R	⊖	Glass Mountain	California
6	R	O	Little Glass Mt.	"
7	pB/pA	●	Mt. Shasta	"
8	B	●	Cinder Cone	"
9	D	●	Lassen Peak	"
10	R	⊕	Steamboat Springs	Nevada
11	B/R	⊖	Coso Hot Springs	California

Mexico

1	oB	●	Volcán de las Tres Vírgenes
2	pT	●	Bárcena (Boquerón)
3	pA	●	Ceboruco
4	pA/A	●	Colima
5	oA/pA	●	Parícutin
6	oB	●	Jorullo
7	R	⊕	Sierra de San Andrés
8	oB	●	Xitli
9	pA	●	Popocatépetl
10	pA/hA	●	Pico de Orizaba
11	oB	●	Volcán de San Martín
12	hA	⊖	El Chichón
13	pA/hA	●	Tacaná

2

3

Guatemala

1	pA/hA	●	Tacaná
2	pA	●	Tajumulco
3	oA/pA	●	Santa Maria
4	hA	●	Cerro Quemado
5	oB	●	Zuñil
6	A	●	Atitlán
7	pA/D	⊖	Toliman
8	pA	●	Acatenango
9	oA/pA	●	Fuego
10	pA	⊖	Agua
11	oA/B/D	●	Pacaya
12	pA	⊖	Tecuamburro

El Salvador

1	pA	●	Ahuachapán
2	oB/pA	●	Santa Ana
3	oB	●	Izalco
4	oB	●	San Marcelino
5	oB/pA	●	San Salvador
6	pA/hA/D	●	Islas Quemadas
7	pA	⊖	San Vicente
8	oB	⊖	Tecapa
9		●	Chinameca
10	oB	●	San Miguel
11	pA	⊖	Conchagua
12	B	●	Conchaguita

Nicaragua

1	pB/A	●	Coseguina
2	B	●	El Viejo
3	B/A	●	Chichigalpa
4	B	●	Telica
5	oB/pB	●	Santa Clara
6	oB/pA	●	Hervideros de San Jacinto y Tisate
7	oB	●	Cerro Negro
8	B	●	Las Pilas
9	B	●	Momotombo
10	oB/pB	●	Masaya
11	B	●	Mombacho
12	B	●	Concepción

9	B	●	Momotombo
10	oB/pB	●	Masaya
11	B	●	Mombacho
12	B	●	Concepción

<u>Costa Rica</u>

1	A	●	Orosí
2	A	●	Rincón de la Vieja
3	A	Θ	Miravalles
4	B	●	Poas
4a		O	Arenal
5	oB	●	Barba
6	B	●	Irazú
7	B/A	●	Turrialba

<u>Galápagos Islands</u>

1	oB	●	Isla Fernandina	Isla Fernandina
2		●	Volcan Wolf	Isla Isabela
3	poB	●	Volcan Darwin	"
4	pB	●	Volcan Alcedo	"
5	pB	●	Sierra Negra	"
6		●	Cerro Azul	"
7	oB	●	Isla Pinta	Isla Pinta
8	B	●	Isla Marchena	Isla Marchena
9	oB/A	●	Isla San Salvador	Isla San Salvador
10	opB	●	Isla Santa Maria	Isla Santa Maria
11	B/A	●	Isla Española	Isla Española

<u>Colombia</u>

1	pA	Θ	Mesa Nevada de Herveo
2	A/D	●	Ruiz
3	A/D	●	Tolima
4	A	Θ	Machin
5	A/D	Θ	Huila
6	A/D	●	Puracé
7	A/D	●	Doña Juana
8	A/D	●	Galeras
9	A/D	Θ	Azufral de Túquerres
10	A/D	●	Cumbal
11	A/D	●	Cerro Negro de Mayasquer

Ecuador

1		●	Reventador
2	A/D	●	Guagua Pichincha
3	A/D	●	Antisana
4	B/A	●	Sumaco
5	opA	●	Cotopaxi
6	A/D	●	Quilotoa
7		●	Llanganate
8	opA	●	Tungurahua
9	B/A	●	Sangay

Peru

1	pA/A	θ	El Misti
2	pA	●	Ubinas
3	A	θ	Huaynaputina
4	A	θ	Tutupaca

Chile

1	A	θ	Tacora
2		●	Guallatiri
3		●	Isluga
4		θ	Irruputuncu
5		θ	Olca
6	pA	θ	Oyahue
7		●	San Pedro
8	B/A	●	Hoyada del Tatio
9	opB	θ	Putana
10	A/B	●	Lascar
11	pB	●	Llullaillaco
12	pB	θ	Lastarria
13		θ	Nevado Ojos del Salado
14	pA/oB	●	Tupungatito
15	pA	●	San José
16	T	θ	Tinguiririca
17	pA	●	Peteroa
18	T	●	Descabezado Grande
19	A	●	Cerro Azul
20	oB	●	Nevados de Chillán
21	oB	●	Antuco
22	T	θ	Los Copahues
23		●	Longuimay
24	oB	●	Llaima

21	oB	●	Antuco
22	T	θ	Los Copahues
23		●	Longuimay
24	oB	●	Llaima
25	oB/A	●	Villarrica
26	A	●	Riñihue
27	A	●	Nilahue
28	oB/pA	●	Puyehue
29	pA	●	Osorno
30	pA/	●	Calbuco
31		●	Huequi
32		●	Minchinmávida
33		●	Corcovado
34		θ	Lautaro
34a		●	Mt. Hudson
35	A	●	Monte Burney

<u>Isla San Felix and Islas Juan Fernandez</u>

1	ophB	θ	Isla San Felix
2	oB	○	El Yunque
3		⊙	Submarine
4		⊙	Submarine

<u>New Zealand</u>

1	A	●	White Island
2		●	Mt. Tarawera
3	A	●	Tongariro
4	oA	●	Ngauruhoe
5		●	Ruapehu

<u>Kermadec, Tonga, and Samoa Islands</u> (K,T,S, respectively)

1		θ	Curtis Island, K
2		●	Brimstone Island, K
3	opA	●	Raoul Island, K
4		⊙	Subm. erup. N of Raoul, K
5		⊙	Subm. erup. SW of Tongatabu, T
6		⊙	Subm. erup. NW of Tongatabu, T
7		⊙	Subm. erup. NW of Tongatabu, T
8		⊙	Subm. erup. SE of Honga Hapai, T
9	pA	●	Falcon Island, T
10	pA	●	Tofua Island, T

Rodda, P., 1967, Outline of the geology of Viti Levu: New Zealand Jour.

11		●		Metis Shoal, T
12		●		Home Reef, T
13	A	●		Late Island, T
14	D	●		Fonualei Island, T
15	B/pA	●		Niuafo'ou Island, T
16		⊙		Subm. vol. near Olosega Is.,
17	B	●		Mauga Afi (Savaii), S
18	B	●		Savaii 1902 (Mauga mu), S
19	oB	●		Matavanu (Savaii), S

Melanesian Islands

1	B	●	Tuluman	Admirality Group
2	B	●	Bam	Off NE Coast of New Guinea
3		●	Manam (Vulcan Is.)	"
3a		⊙	Subm. erup. NW of Karkar Is.	"
4		●	Karkar	"
5		⊙	Subm. volcano NNE of Karkar Is.	"
6	B	●	Long Island	"
7	B	θ	Talo	"
8	oB	●	Ritter	"
9	pB	θ	Sakar	"
10	pB	●	Langila	New Britain
11		θ	Narage	"
12	B	●	Garove	"
13	B	●	Benda	"
14		θ	Bola	"
15		θ	Garua	"
16	B	●	Garbuna	"
17	B	●	Pago	"
18		θ	Walo	"
19		θ	Galloseulo	"
20	pB	θ	Bamus	"
21	oB	●	Ulawun	"
22	oB	●	Lolobau	"
23	oB	●	Rabaul	"
	A	●	Vulcan	"
	oB	●	Matupi	"
	pB	θ	Rabalanakaia	"
	pB	●	Sulphur Creek	"
24	pA	●	Lamington	Papua & D'Entrecasteaux Is.
25		θ	Musa River	"

	pB	⊖	Rabalanakaia	"
	pB	●	Sulphur Creek	"
24	pA	●	Lamington	Papua & D'Entrecasteaux Is.
25		⊕	Musa River	"
26		●	Victory	"
27	TA	●	Goropu	"
28		⊕	Iamelele	"
29	T	⊕	Deidei	"
30	TA	⊖	Dobu	"
31		⊕	Lihir	East of New Ireland
32	B/A	⊕	Ambitle	"
33	B	⊖	Balbi	Solomon Islands
34	B/A	●	Bagana	"
35	hA	⊖	Loloru	"
36	pA	⊕	Parasa	"
37	pA	⊖	Simbo	"
37a		⊖	Cook Submarine Vol.	Solomon Islands
38		⊙	Subm. vol. near Eromanga Is.	(S. of Vaguna Is.)
39	hA	●	Savo	"
40		●	Tinakula	Santa Cruz Is.
41	B	⊖	Suretamatia	New Hebrides Is.
42	B	⊖	Gaua	"
43	oB	⊖	Aoba	"
44	opB	●	Ambrym	"
45	pB	●	Lopevi	"
46	opA	⊖	Subm. vol. near Epi Is.	"
47		⊙	Karua	"
48	B/pA	●	Tongoa	"
49		⊙	Subm. vol. near Eromanga Is.	"
50	pA	●	Yasour	"
51	B	●		Matthew Is.
52		⊖		Hunter Is.

Celebes, Sangihe Islands, Halmahera, and Eastern New Guinea

1	pA/hA	●	Una Una	Celebes
2	pA/hA	●	Ambang	"
3	B/opA	●	Soputan	"
4		⊖	Sempu	"
5		●	Batu Kolok	"
6		●	Tempang	"
7	pA	⊕	Tampusu	"
8	pA	⊕	Lahendong	"

Geologic data on the numerous islands are based on many literature sources.

3

9	A	⊕	Sarangsong	"
10	oB/pA	●	Lokon-Empung	"
11	B/pA	●	Mahawu	"
12	op/A	⊖	Klabat	"
13	pA	●	Tongkoko	"
14	B/pA/hA	●	Ruang	Sangihe Islands
15	pA	●	Api Siau	"
16	pA/hA	●	Banua Wuhu	"
17	phA	●	Awu (Awa)	"
18		⊖	Submarine Volcano	"
19	oB/pA	●	Dukono	Halmahera
20		●	Malupang Warirang	"
21		●	Ibu	"
22		●	Gamkonora	"
23		⊖	Todoko	"
24	oB/pA	●	Peak of Ternate Motir	"
25	pA	●	Makian	"
26		●	Umsini	Eastern New Guinea

<u>Lesser Sunda Islands and Banda Sea</u>

1	pA/hA	●	Batur
2	pA	●	Agung
3		●	Rindjani
4	lBa	●	Tambora
5	oB/pA	●	Sangeang Api
6		⊕	Wai Sano
7		⊕	Potjo Leok Caldera
8	pA	⊖	Ineri
9		●	Inie Lika
10	B	●	Amburombu
			Pui
11	oB/pA	●	Ija
12		⊕	Sukaria Caldera
13		⊕	Ndetu Napi
14	pA	●	Kelimuta
15	pA	●	Paluweh
16	pA	●	Egon
17	pA	⊖	Ili Muda
18	pA	●	Lewotobi Laki-Laki
19	oB/pA	●	Lewotobi Perampuan
20	pA/hA	●	Leroboleng
21		⊕	Riang Kotang
22	pA	●	Ili Boleng

17	pA	⊖	Ili Muda
18	pA	●	Lewotobi Laki-Laki
19	oB/pA	●	Lewotobi Perampuan
20	pA/hA	●	Leroboleng
21		⊕	Riang Kotang
22	pA	●	Ili Boleng
23	oB/pA	●	Lewotolo
24	B/pA	⊖	Labalekan
25	B/pA	●	Ili Werung
26	lBa	●	Batu Tara
27	B/pA	●	Sirung
28		●	Yersey Volcano
29		●	Emperor of China
30		●	Nieuwerkerk
31	oB/pA	●	Api, N of Wetar
32	opA	●	Damar
33		●	Teon
34	pA	●	Nila
35	pA	●	Serua
36		⊖	Manuk
37	pA	●	Banda Api

<u>Java</u>

1	B/pA	⊖	Pulosari
2	B/pA	⊖	Karang
3		⊕	Kiaraberes Gagak
4	pA	⊕	Perbakti
5	B/pA	●	Salak
6	B/pA	●	Gedeh
7	pA	⊖	Patuha
8	pA	⊖	Wajang Windu
9	pA	●	Tangkuban Prahu
10	opA	●	Papandajan
11	pA	⊕	Kawah Manuk
12	pA	⊕	Kawah Kamodjang
13	B/pA	●	Guntur
14	B/pA	●	Galunggung
15	B/pA	⊖	Telaga Bodas
16		⊕	Kawah Karaha
17	opA	●	Tjerimai
18	B/pA	●	Slamet
19	pA	●	Butak Petarangan

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20	B/pA	●	Dieng
21	pA	●	Sundoro
22	pA	●	Sumbing
23	oB/pA/hA	ϴ	Ungaran
24	oB/pA	●	Merbabu
25	oB/pA	●	Merapi
26	pA	ϴ	Lawu
27	pA	ϴ	Wilis
28	pA	●	Kelut
29	oB/pA	ϴ	Ardjuno Welirang
30	oB/pA	●	Semeru
31	oB/pA	●	Bromo
32	oB	●	Lamongan
33	oB/opA/hA	ϴ	Ijang Argapura
34	B/A	●	Raung
35	pA	●	Kawah Idjen

<u>Sumatra</u>

1	hA	⊕	Pulu-Weh
2	phA	●	Silawaih Agam
3		●	Peuetsagoe
4	A	ϴ	Bur ni Geureudong
5		●	Bur ni Telong
6	B/pA	⊕	Gajolesten fields
7	A	ϴ	Sibajak
8	A	ϴ	Sinabung
9	pA	ϴ	Pusuk Bukit
10	pA	⊕	Helatobo-Tarutung
11	phA	ϴ	Bual Buali
12	phA	●	Sorikmarapi
13	pA	ϴ	Talakmau
14	pA	●	Merapi
15	pA	●	Tandikat
16	pA	●	Talang
17	A	●	Kerintji
18	A/D	●	Sumbing
19		ϴ	Kunjit
20	B/pA	ϴ	Blerang Beriti
21	pA	ϴ	Bukit Daun
22	pA	●	Kaba
23	pA	●	Dempo
24	pA	●	Lumut Balai

21	pA	⊖	Bukit Daun	
22	pA	●	Kaba	
23	pA	●	Dempo	
24	pA	●	Lumut Balai	
25	B/A	⊕	Marga Bajur	
26	pA	⊖	Sekintjau Belirang	
27		⊕	Pematang Bata	
28	B/A	⊕	Hulubelu	
29	pA	⊖	Radjabasa	
30	pA	●	Krakatau	

<u>Philippine Islands</u>

1	B	●	Jolo	
2		●	Balut	
3	A	⊖	Matutum	Mindanao
4	hA	⊖	Apo	"
5		⊖	Makaturing	"
6		⊖	Latukan	"
7		●	Ragang	"
8		●	Calayo	"
9	pA	●	Catarman	
10	B/A	⊖	Magaso	Negros
11	B/A	●	Canlaon	"
12		⊖	Mandalagan	"
13		⊖	Silay	"
14		●	Cabalian	Leyte
15	A	⊕	Danan	"
16	hA	⊖	Kasiboi	"
17	hA	⊕	Biliran	
18	B/A	●	Bulusan	Luzon
19	A	⊖	Pocdol Mts	"
20	pA	●	Mayon	"
21	B/A	⊖	Malinao	"
22	A	●	Banahac	"
23	B	⊖	Maquiling	"
24	pA	●	Taal	"
25	A	⊕	Jalajala	"
26		●	Cagua	"
27		●	Camiguin de Babuyanes	
28		●	Didicas	
29	B	●	Smith	
30	B	●	Babuyan Claro	
31		⊙	Subm. near Ibugos	

Ryukyu, Japanese, Izu, Bonin, and Mariana Islands

1		○	Subm. erup.	E and N of Taiwan
2		⊙	" "	"
3		⊙	" "	"
4		⊙	" "	"
5		⊙	" "	"
6		⊙	Temp. subm. erup.	Ryukyu Is.
7	pA	●	Okinawa - Tori-sima	"
8	poA	●	Suwanose-zima	"
9	pA/pD/hqD	●	Nakano-sima	"
10	oB/pA	●	Kutinoerabu-zima	"
11	pD/opA	●	Tokara - Iwo-zima	"
12	oB/opA	●	Kaimon	"
13	pA	●	Sakura-zima	"
14	pA/hpA	●	Kirisima	"
15	phA/hA/ bhA/bhD	●	Unzen	"
16	pA/pR, D/pA	●	Aso	"
17	pA/ahA/pA	⊖	Kuzyu	"
18	nA	⊖	Turumi	"
19	oB/oA/pA	⊕	Omuro-yama	Honshu
20	oB/pA/pD	⊖	Hakone	"
21	oB/opB	●	Huzi	"
22	pA/opA/hpA	⊖	On-take	"
23	hpA	●	Haku-san	"
24	hpA	⊖	Norikura	"
25	pbhA	●	Yake-dake	"
26	hpA/pA	⊖	Midagahara	Honshu
27	ohpA	●	Niigata-Yake-yama	"
28	phnA	⊖	Myōkō	"
29	pA/opA	●	Asama	"
30	pA	●	Kusatu-Sirane	"
31	pA	●	Akagi	"
32	opqhA	●	Nikkō-Sirane	"
33	pB/pA	●	Nasu	"
34	pA	●	Bandai	"
35	pA	●	Adatara	"
36	pA	●	Azuma	"
37	opA/hpqD	●	Zaō	"
38	pD	⊖	Narugo	"

34	pA	●	Bandai	"
35	pA	●	Adatara	"
36	pA	●	Azuma	"
37	opA/hpqD	●	Zaō	"
38	pD	⊖	Narugo	"
39	opA	●	Kurikoma	"
40	opA	●	Tyōkai	"
41	opB/opA	●	Akita - Komaga-take	"
42	pA/oB/pA	●	Iwate	"
43	opB/opA/pA	⊖	Hatimantai	"
44	pA/D	●	Akita - Yake-yama	"
45	pA	●	Iwaki	"
46	pA	⊖	Hakkōda	"
47	pA/hD	⊖	Osore-yama	"
48	poB/D	●	O-sima	Izu Is.
49	oB/hR/hbR/bR	●	Nii-zima	"
50	R/phbR	●	Kōzu-sima	"
51	oB/poB/pB/ opA/pA	●	Miyake-zima	"
52	opB	●	Hatizyō-zima	"
53	oB/A	●	Aoga-sima	"
53a		⊙	Myozin-syo	"
54	pB/paD	●	Bayonnaise	"
55		⊙	Smith Rock	"
56	poB/poA	●	Tori-sima	"
57		⊙	Temp. subm. erup.	Bonin Is.
57a		⊙	Nishino-Shima subm.	"
58		●	Kita - Iwō-zima	"
59	poTA	●	Iwō-zima	"
60	opTA	●	Sin - Iwō-zima	"
61	opA	●	Uracas	Mariana Is.
61a		⊙	Pacific sub. vol.	"
62		●	Assoqsong	"
63	oB/opB/pB	●	Agrigan	"
64	oB/pA/opB	●	Pagan	"
65	poB	⊖	Alamagan	"
66	pA	●	Guguan	"
67		⊖	Anatahan	"
68		⊙	Temp. subm. erup.	"
69	opB/opBhA	●	Osima - O-sima	Hokkaido
70	pA	●	Komaga-take	"
71	opA/pD	●	Usu	"
72	pA	●	Tarumai	"

73	poA/phbA	●	Tokati	"
74	A	⊖	Daisetu	"
75	B/pA	●	Me-Akan	"
76	poA/pD	⊖	Atosanupuri	"
77	pA	⊖	Siretoko - Iwō-zan	"

<u>Kurile Islands</u>

1	pA	●	Golovnin Caldera	Kunashir Is.
2	pA	●	Mendeleev	"
3	A	●	Tiatia	"
4	A	⊖	Berutarube	Ilurup Is.
5	A	●	Atsonupuri	"
6	pA	⊖	Ivan Grozny	"
7	pA	⊖	Tebenkov	"
8	A/D	●	Baransky	"
9	A	●	Chirip	"
10	A	●	Kudriavy	"
11		●	Kolokol	Urup Is.
12	A	●	Berg	"
13		⊖	Trezubetz	"
14	A	⊖	Brat Chirpoev	Brat Chirpoev Is.
15		●	Snow	Chirpoi Is.
16		●	Cherny	"
17	A/B	●	Goriaschaia	Simushir Is.
18	A/B	●	Zararitzky	"
19	A	●	Prevo	"
20	A	●	Pallas	Ketoi Is.
21		●	Ushishir	Ushishir Is.
22	pA	●	Rasshua	Rasshua Is.
23		⊖	Subm.	Matua Is.
24	pA	●	Sarychev	"
25		●	Raikoke	Raikoke Is.
26	A/D	●	Chirinkotan	Chirinkotan Is.
27	A	●	Ekarma	Ekarma Is.
28	pA/hA	●	Kuntomintar	Shiashkotan Is.
29	A	●	Sinarka	"
30	pA	●	Severgin	Harimkotan Is.
31	pA/B	●	Krenitzyn	Onckotan Is.
32	pA	●	Nemo	"
33		●	Asyrmintar	"
34	pA/hA	●	Fuss	Paramushir Is.
35	pA	●	Karpinsky	"

30	pA	●	Severgin	Harimkotan Is.
31	pA/B	●	Krenitzyn	Onckotan Is.
32	pA	●	Nemo	"
33		●	Asyrmintar	"
34	pA/hA	●	Fuss	Paramushir Is.
35	pA	●	Karpinsky	"
36	A	⊖	Tatarinov	"
37	pA	●	Chikurachki	"
38	pA	●	Ebeko	"
39	B/A	●	Alaid	Alaid Is.

Kamchatka

1		⊖	Kambalny
2	B/pA	●	Koshelev
3	A	●	Iliinsky
4	B/A	●	Zheltovsky
5	B/A/D	●	Ksudach
6	B/A/D	●	Mutnovsky
7	pA	●	Gorely Khrebet
8	pA/D	●	Opala
9	A/B	●	Koriaksky
10	pA/hA	●	Avachinsky
11	pA/hA	●	Dzenzursky
12	B/pA	●	Zhupanovsky
13	D	●	Karymsky
14	B	●	Maly Semiachik
15	B/A	⊖	Zentralny Semiachik
16	B/A	⊖	Burliastchy
17	B/pA/D/R	⊖	Uzon
18	A/D/R	⊖	Kikhpinych
19	B/pA	●	Krasheninnikov
20		●	Kronotzky
21	B/pA	⊖	Gamchen
22		⊖	Komarova
23	pA/hA	●	Kizimen
24	oB/pB/pA	●	Plosky Tolbachik
25	pA/hA	●	Bezymianny
26	oB/pB	●	Kliuchevskoi
27	B/pA/hA	●	Sheveluch
28	B/A	⊖	Ichinsky

HEAT FLOW IN PACIFIC REGION

PLATES IV, VIII, XII, XVI

Location of heat flow measurement is a dot, beside which is the heat flow value in heat flow units.

One heat flow unit (HFU) is 10^{-6} μcal/cm^2/sec. World-wide average heat flow is about 1.5 HFU.

The heat flow data, complete to about midyear 1973, were supplied by Professor Roger N. Anderson of Lamont-Doherty Geological Laboratory, Columbia University.

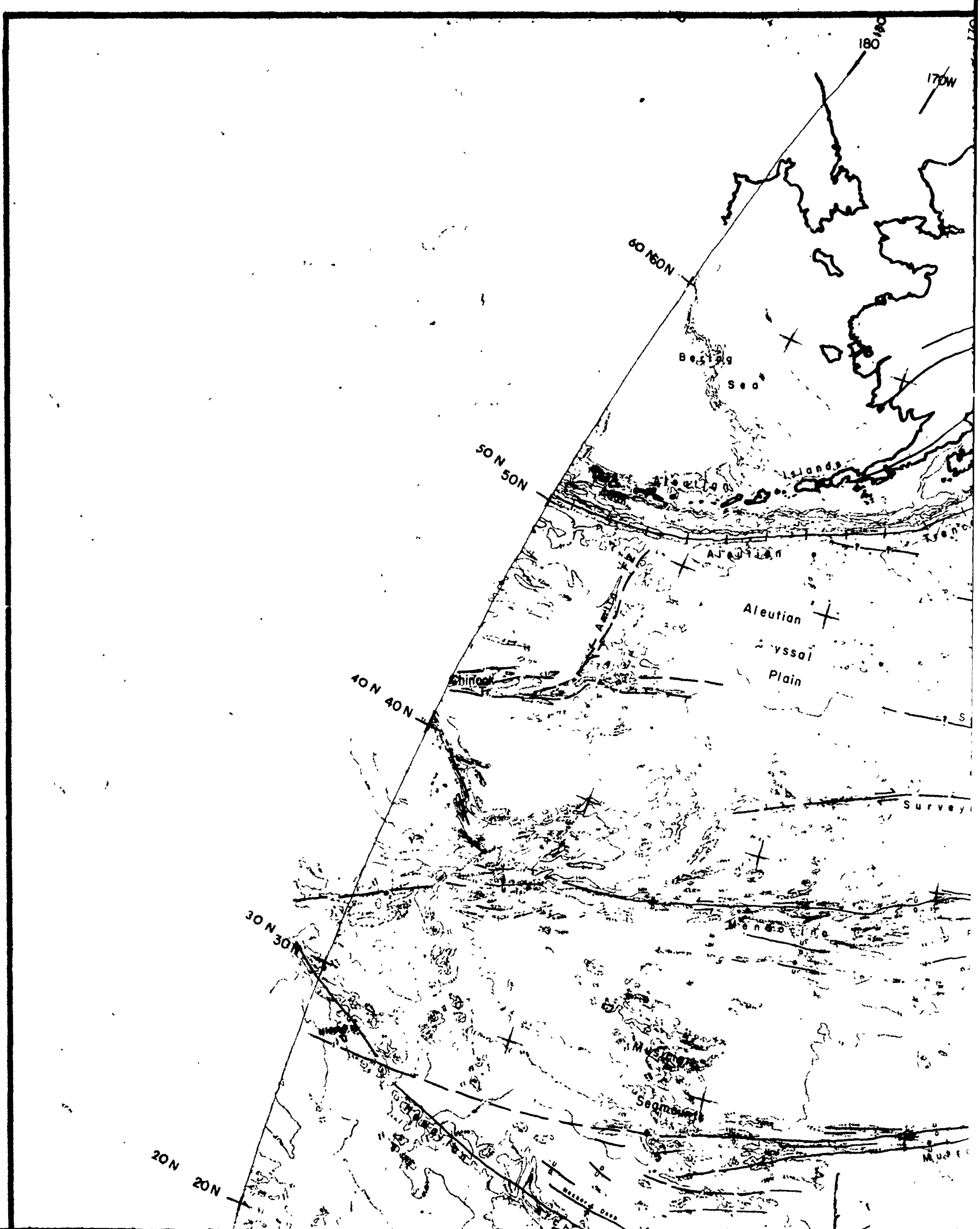
THERMAL SPRINGS IN PACIFIC REGION

PLATES V, IX, XIII, XVII

Thermal springs are indicated as three types according to temperature as follows:

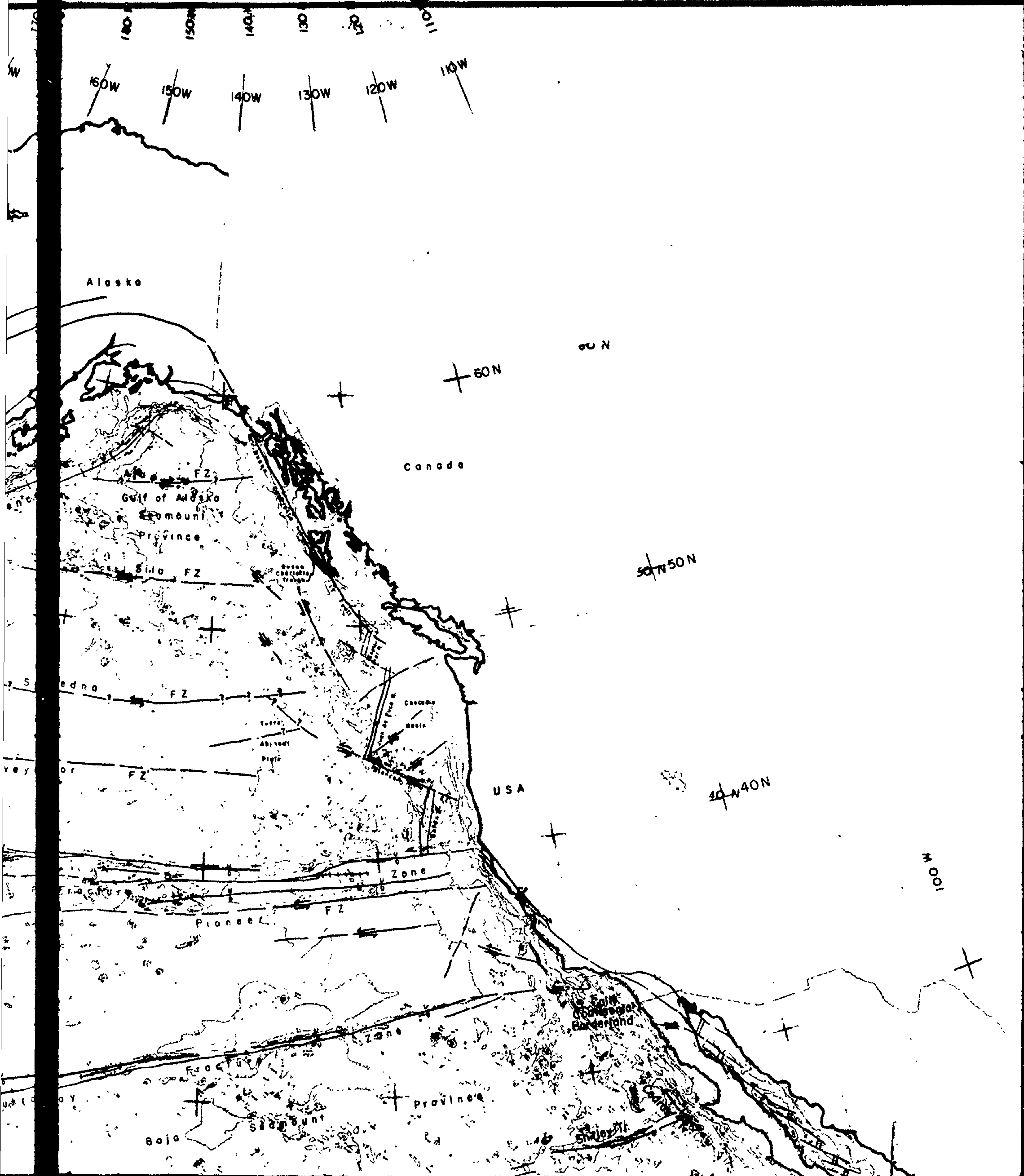
- • **Warm**, $<50^{\circ}$C (122°F)
- \+ Hot, $>50^{\circ}$C $<100^{\circ}$C (122°F - $<212^{\circ}$F)
- * Boiling, $\pm 100^{\circ}$C (212°F)

Thermal spring data were obtained from Waring (1965).



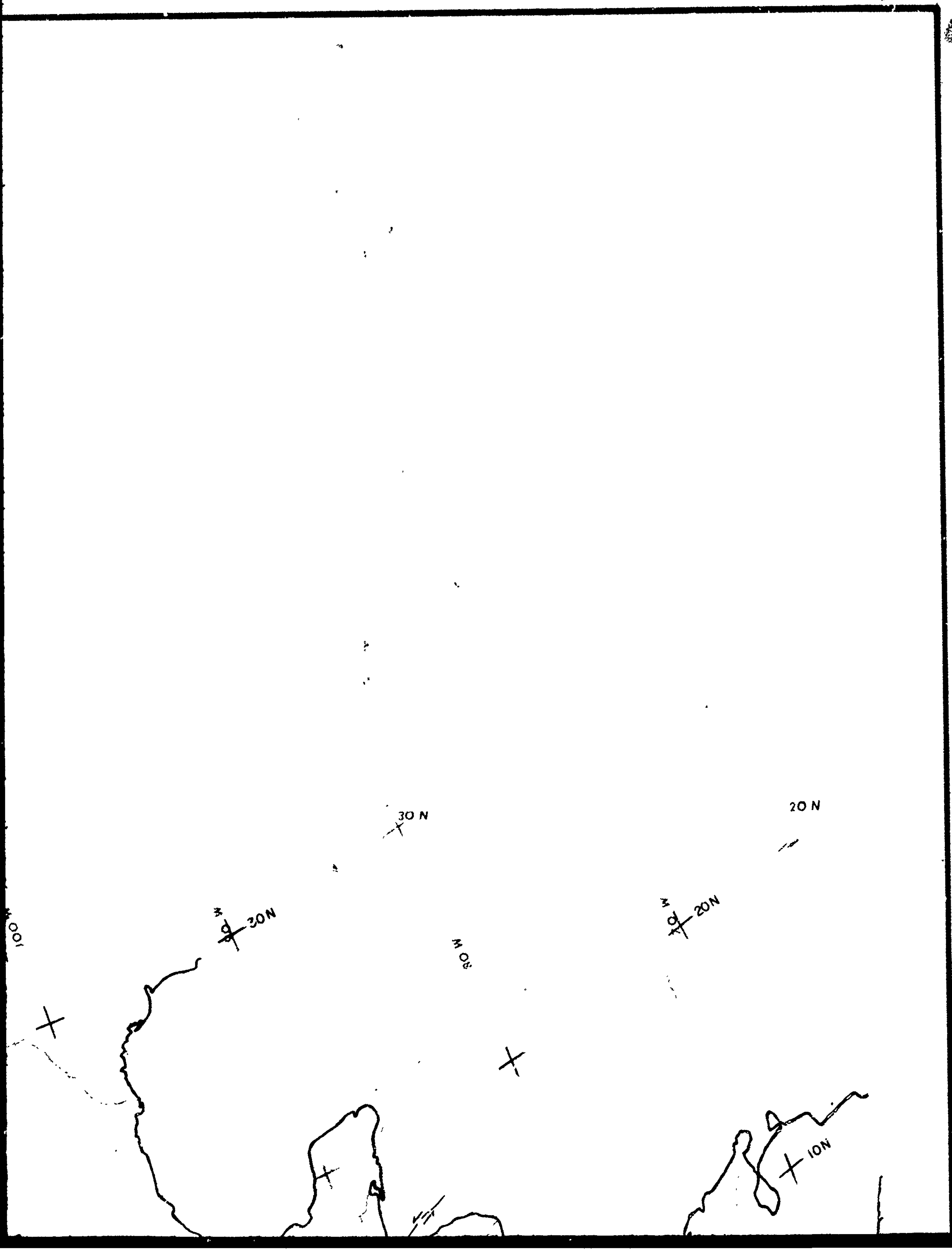
180
170W
60 N
60N
Bering
Sea
50 N
50N
Aleutian
Islands
Aleutian
Trench
Aleutian
Abyssal
Plain
Chinook
40 N
40N
Surveyor
Mendocino
30 N
30N
Musicians
Seamounts
20N
20N

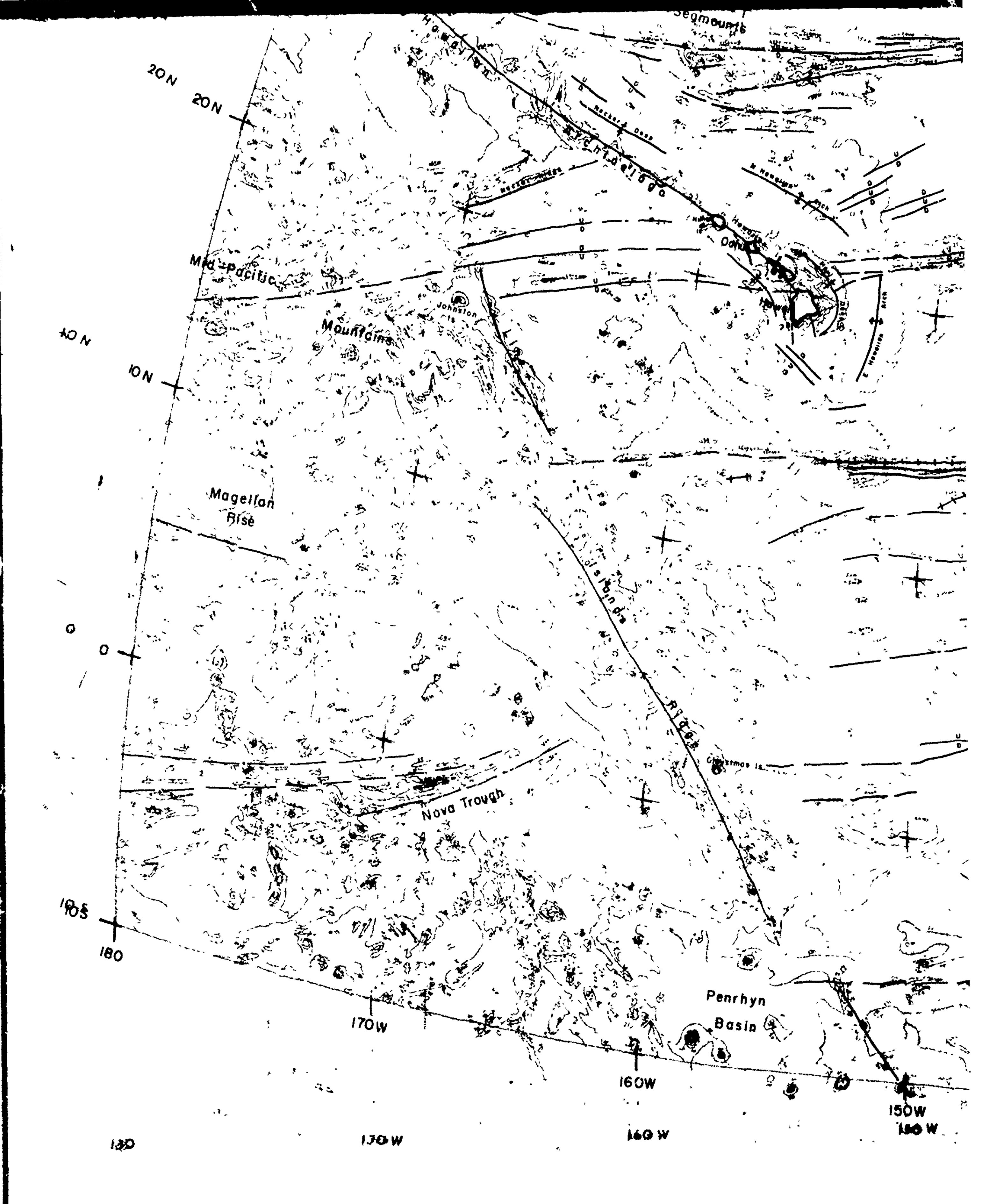
2



160W
150W
140W
130W
120W
110W
Alaska
Canada
60 N
50 N
40 N
USA
Gulf of Alaska
Seamount
Province
FZ
Zone
Pioneer
Fracture
Province
Seamount
Baja

3

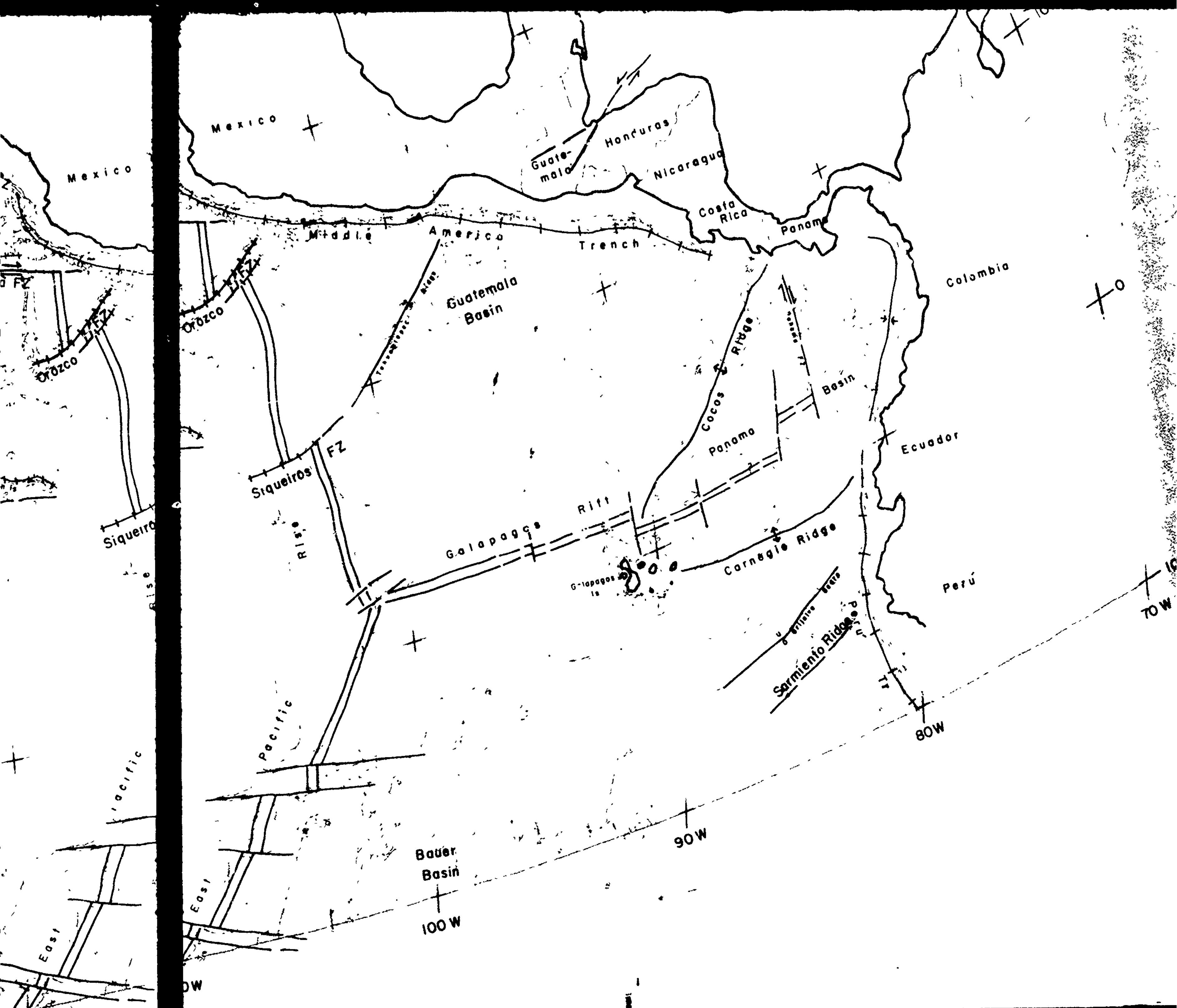



Seamounts
Hawaiian
Archipelago
Necker Deep
Necker Ridge
Oahu
Hawaii
Mid-Pacific
Mountains
Johnston Is.
Line
Islands
Ridge
Christmas Is.
Magellan
Rise
Nova Trough
Penrhyn
Basin
20 N
10 N
0
10 S
180
170 W
160 W
150 W

4

Baja
Seamount
Province
Shirley FZ
Tamayo FZ
Zone
Fracture
Molokai
Rivera FZ
Clarion
Zone
Fracture
Clarion
Orozco
Clipperton Is.
Zone
Fracture
Clipperton
Zone
Fracture
Galapagos
East
Marquesas Is.
Marquesas
FZ
110W
150W
140W
130W
120W
110W
5

22 pA Ili Boleng



Northeastern Pacific Region

TECTONIC FEATURES

Plate II

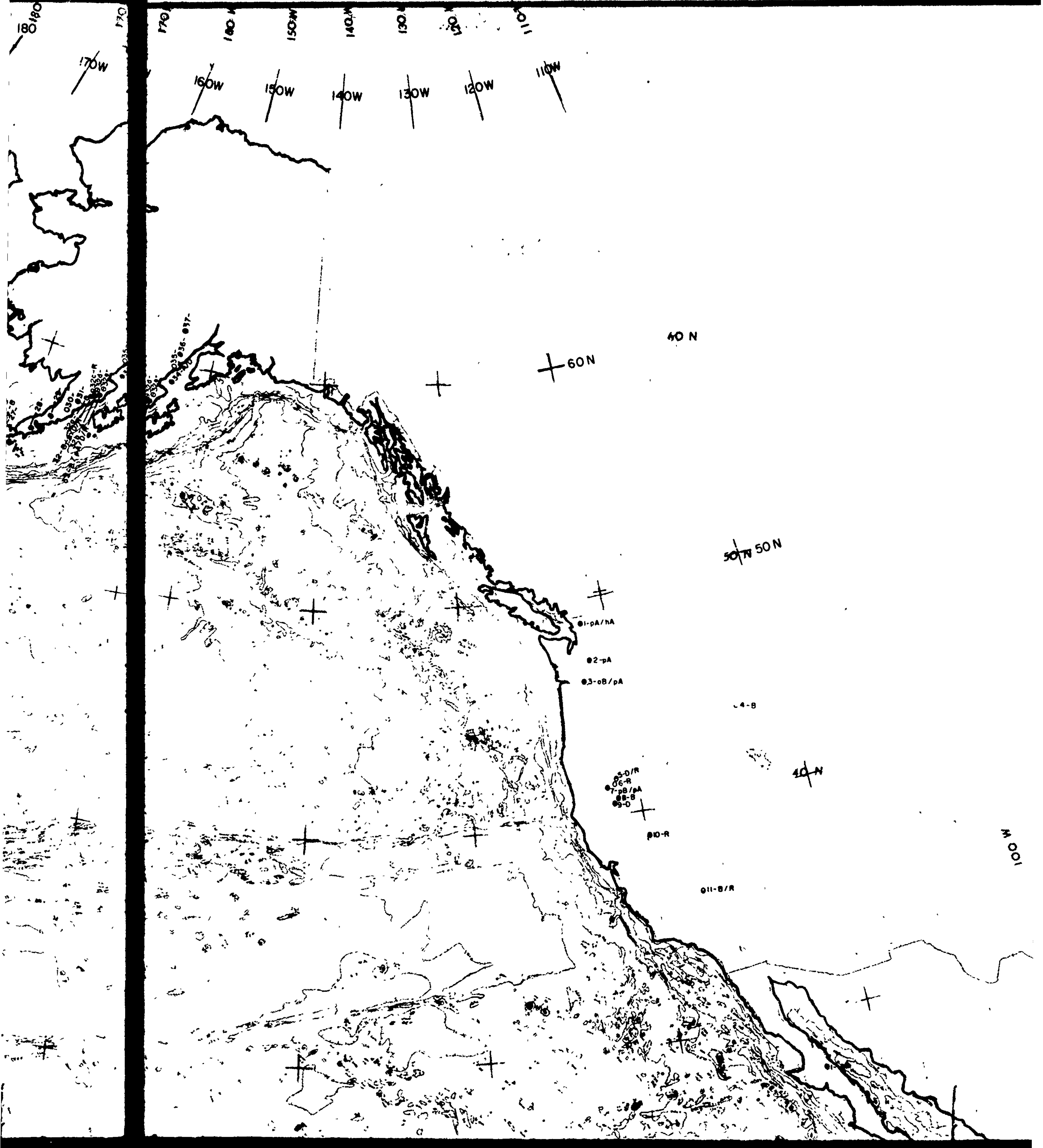
6

gion

ES

I

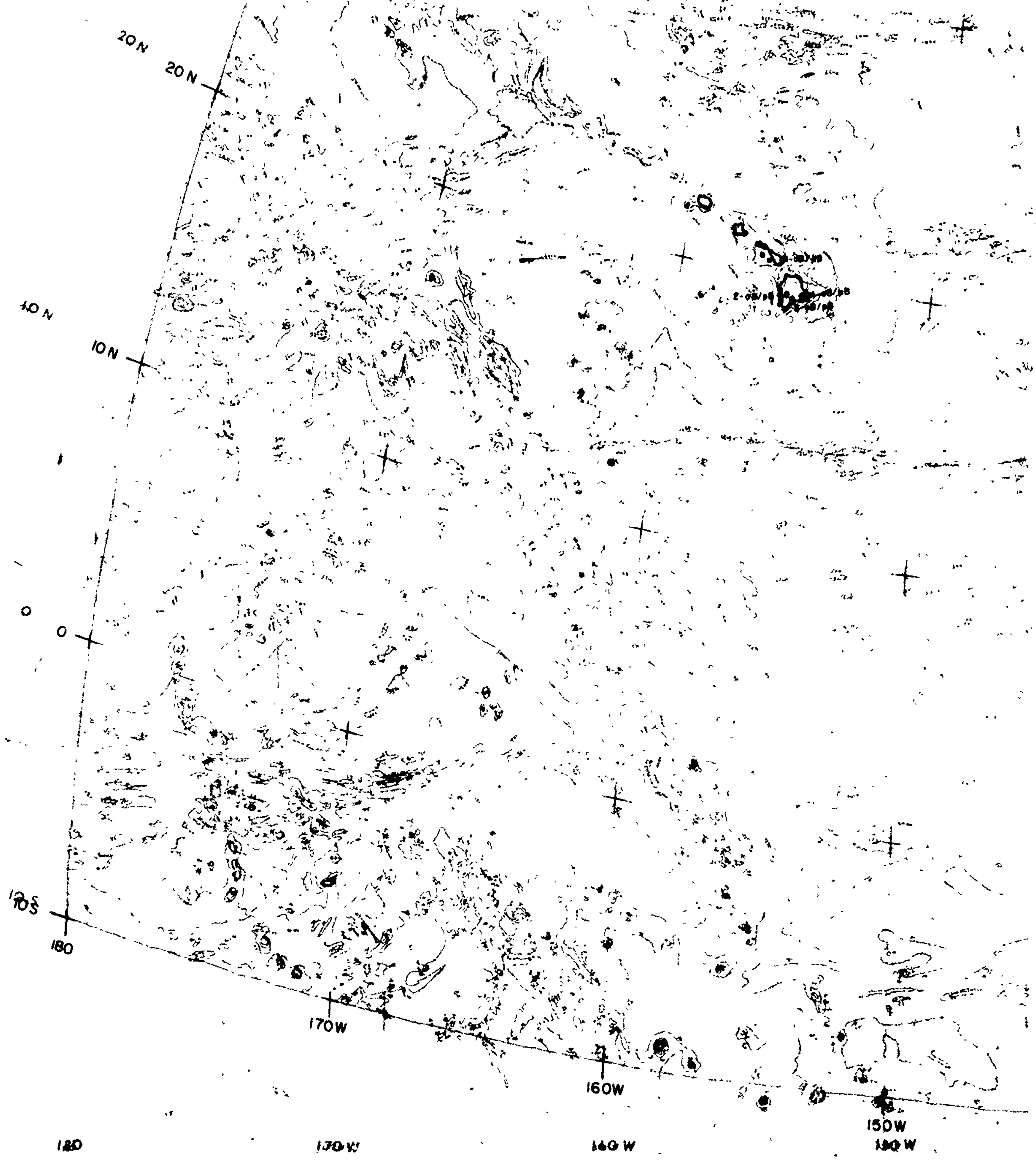
2



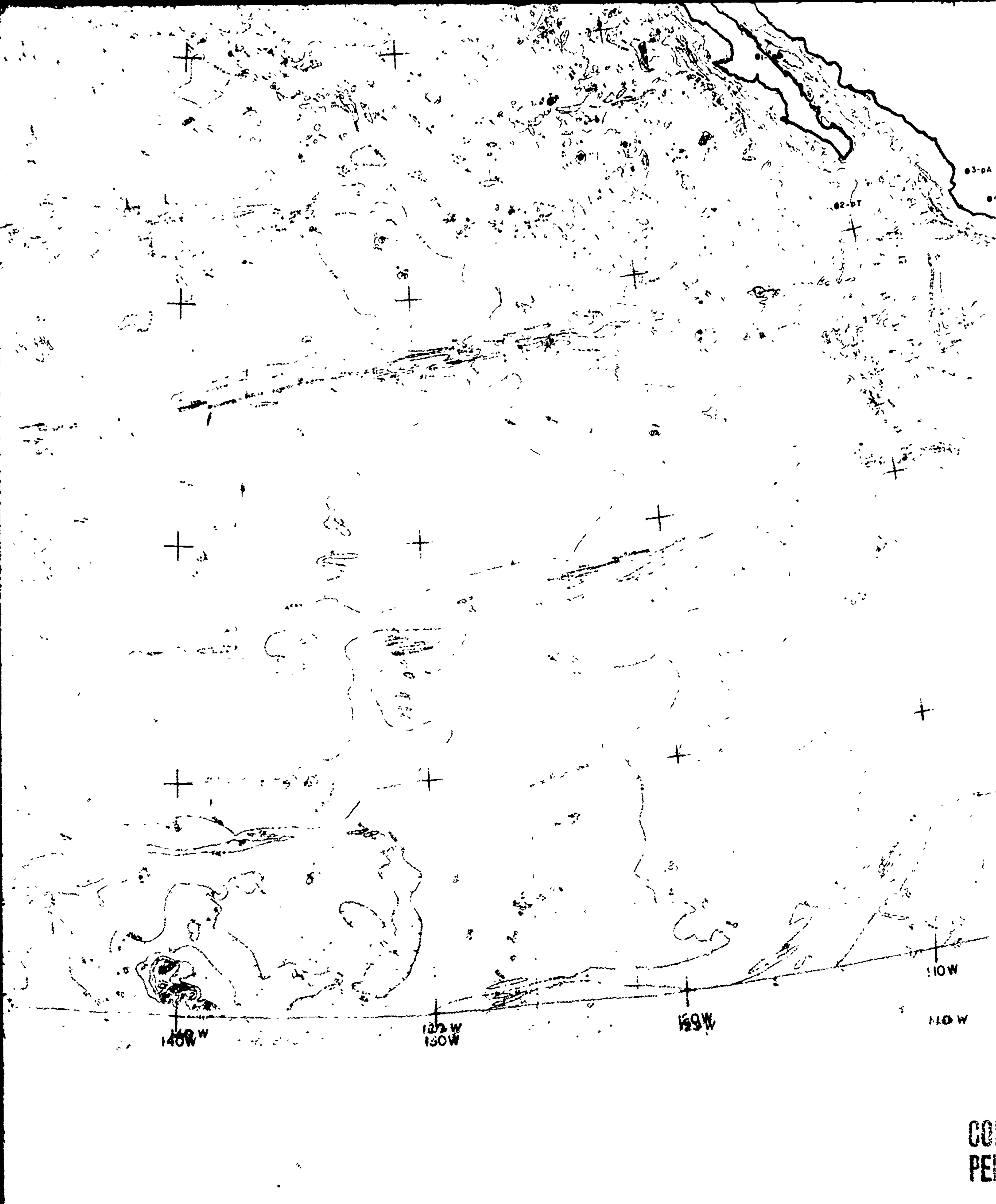
170W
160W
150W
140W
130W
120W
110W
60N
40 N
50 N
40 N
1-pA/hA
2-pA
3-oB/pA
4-B
5-D/R
6-R
7-pB/pA
8-B
9-D
10-R
11-B/R

3

3

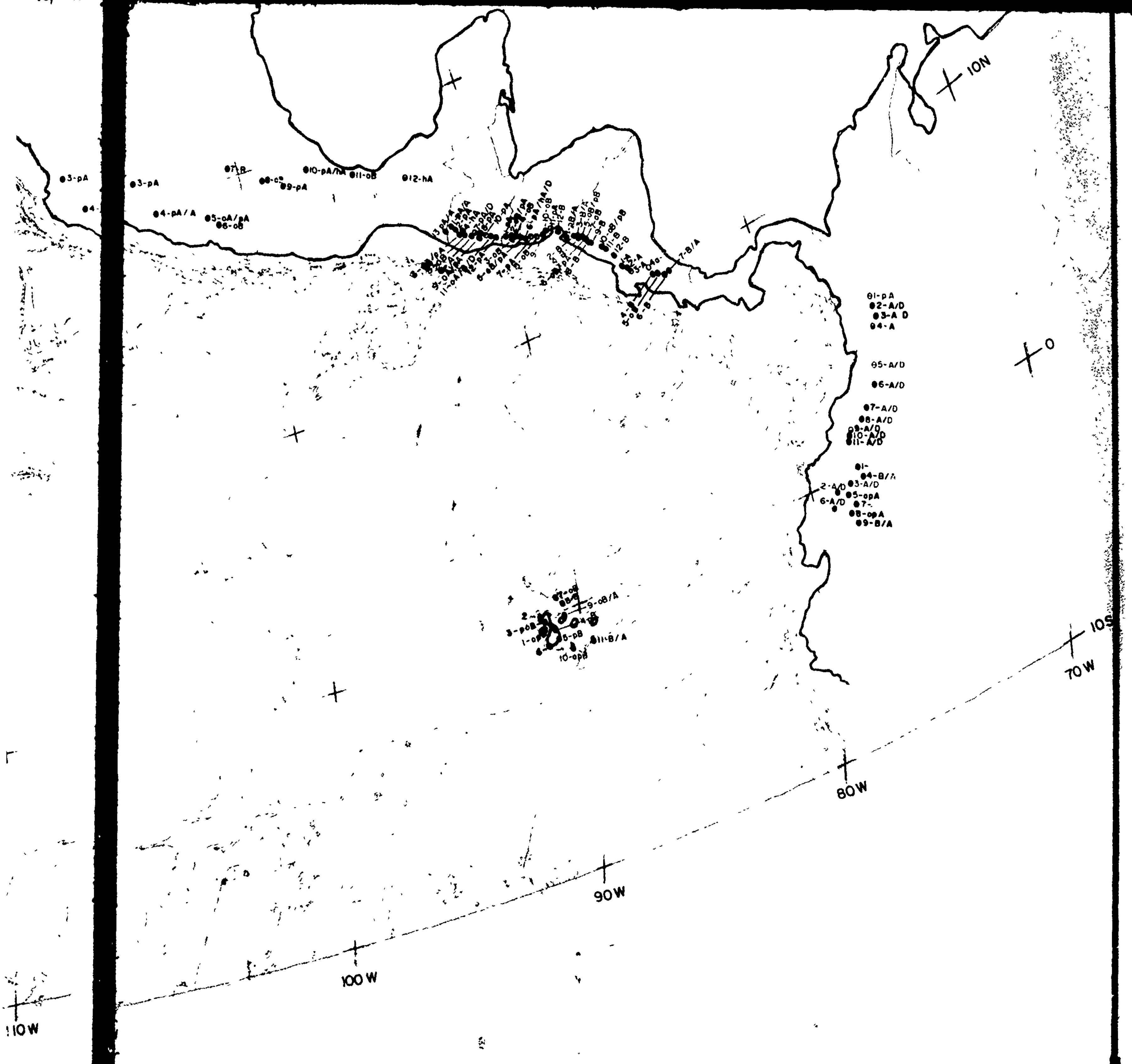


4



CO
PE

5

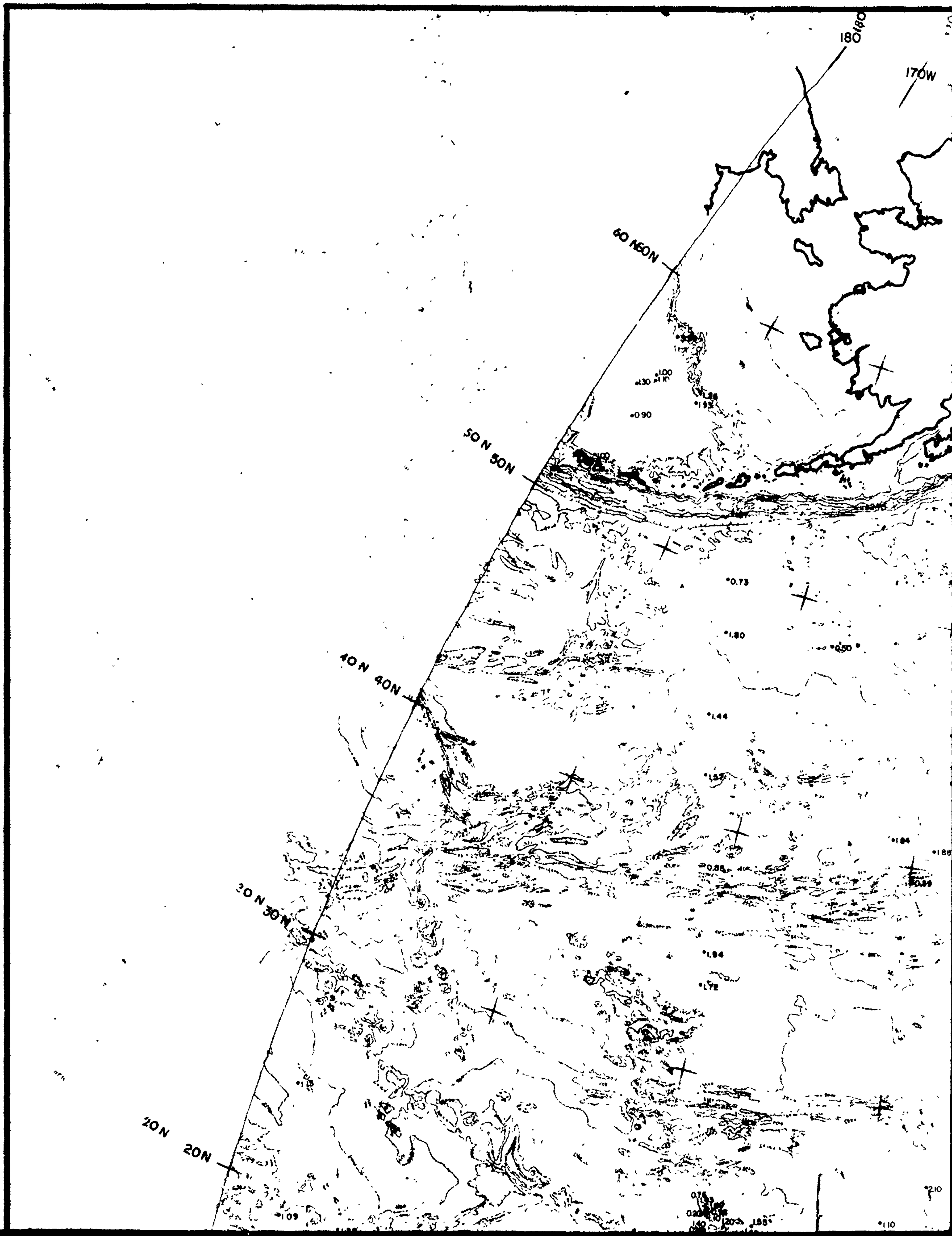


Northeastern Pacific Region

ACTIVE VOLCANOES

Plate III

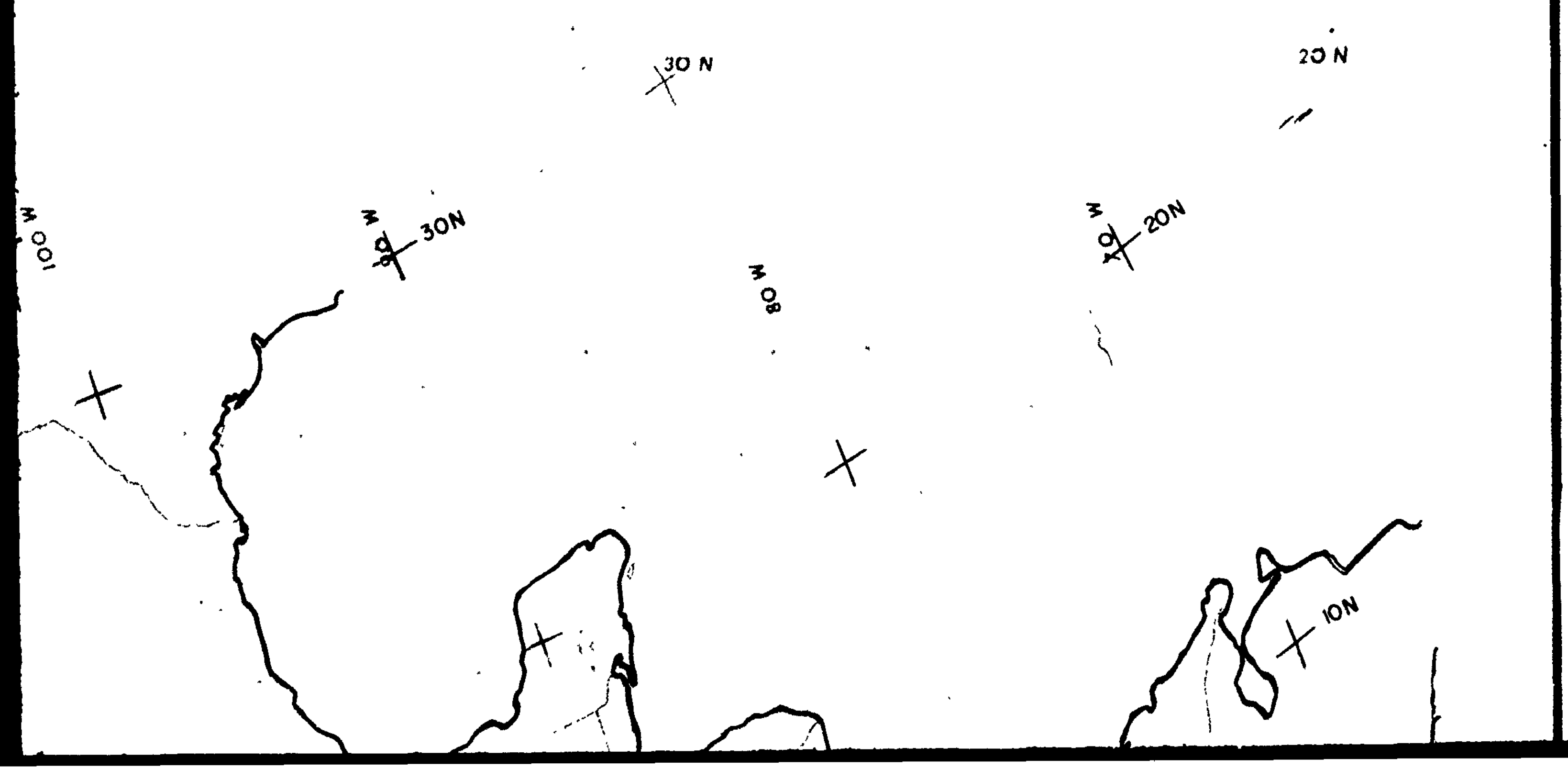
6

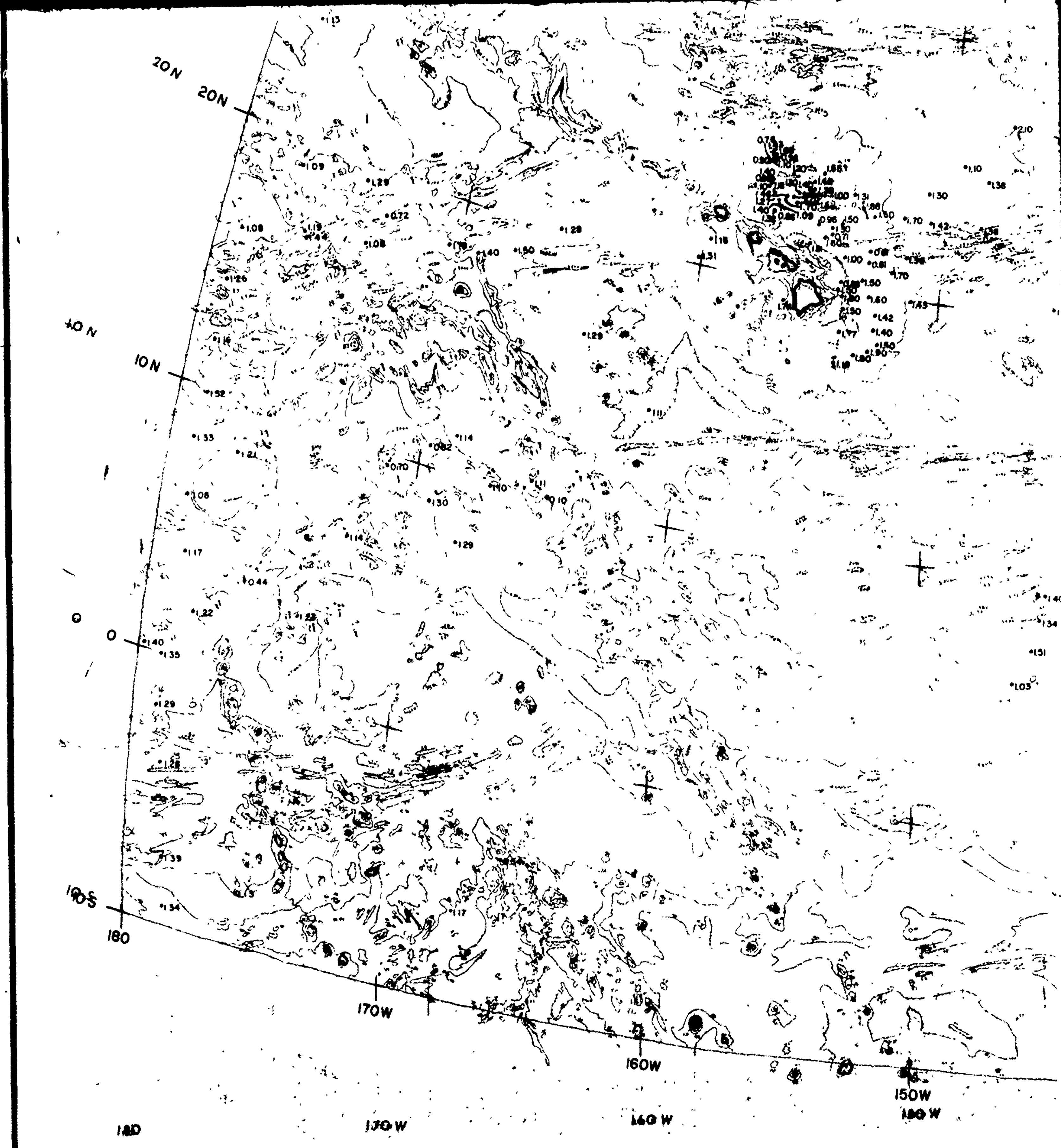


180
180
170W
60 N
60N
50 N
50N
40 N
40N
30 N
30N
20N
20N
•0.90
•0.73
•1.80
•0.50
•1.44
•1.84
•1.88
•0.88
•1.84
•1.72
•1.09
•2.10
•1.10

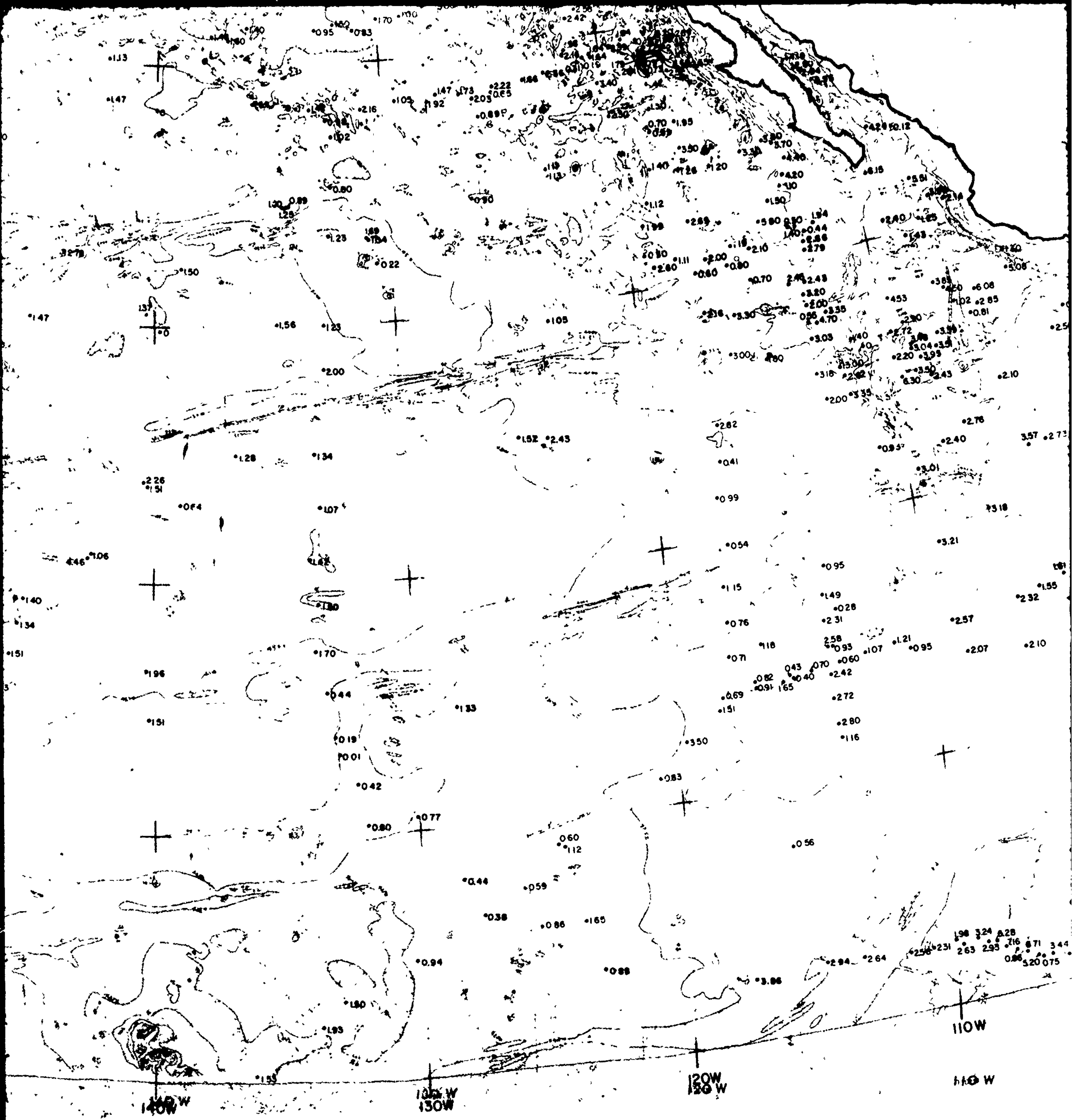
2

3

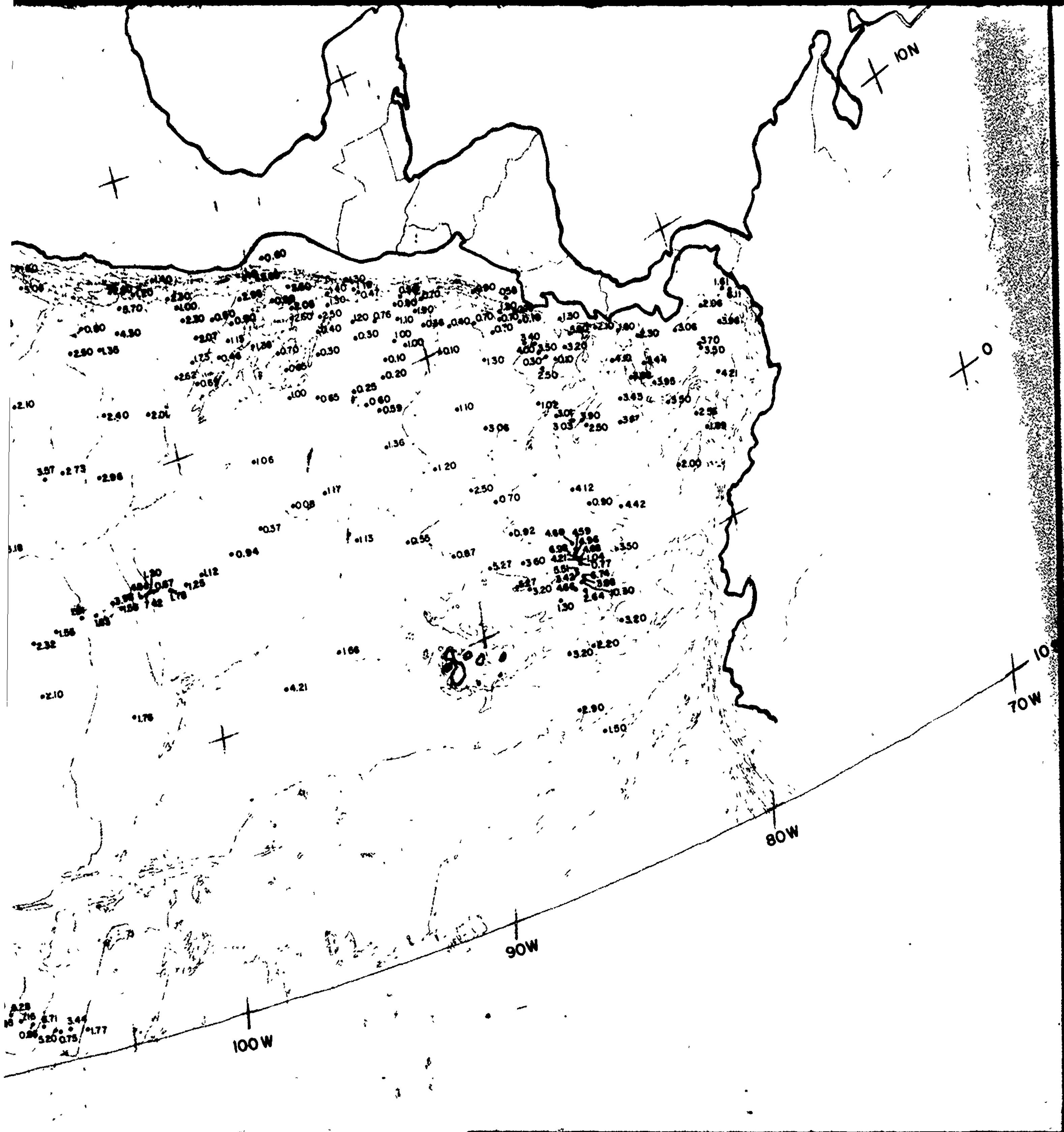




4



140W
130W
120W
110W



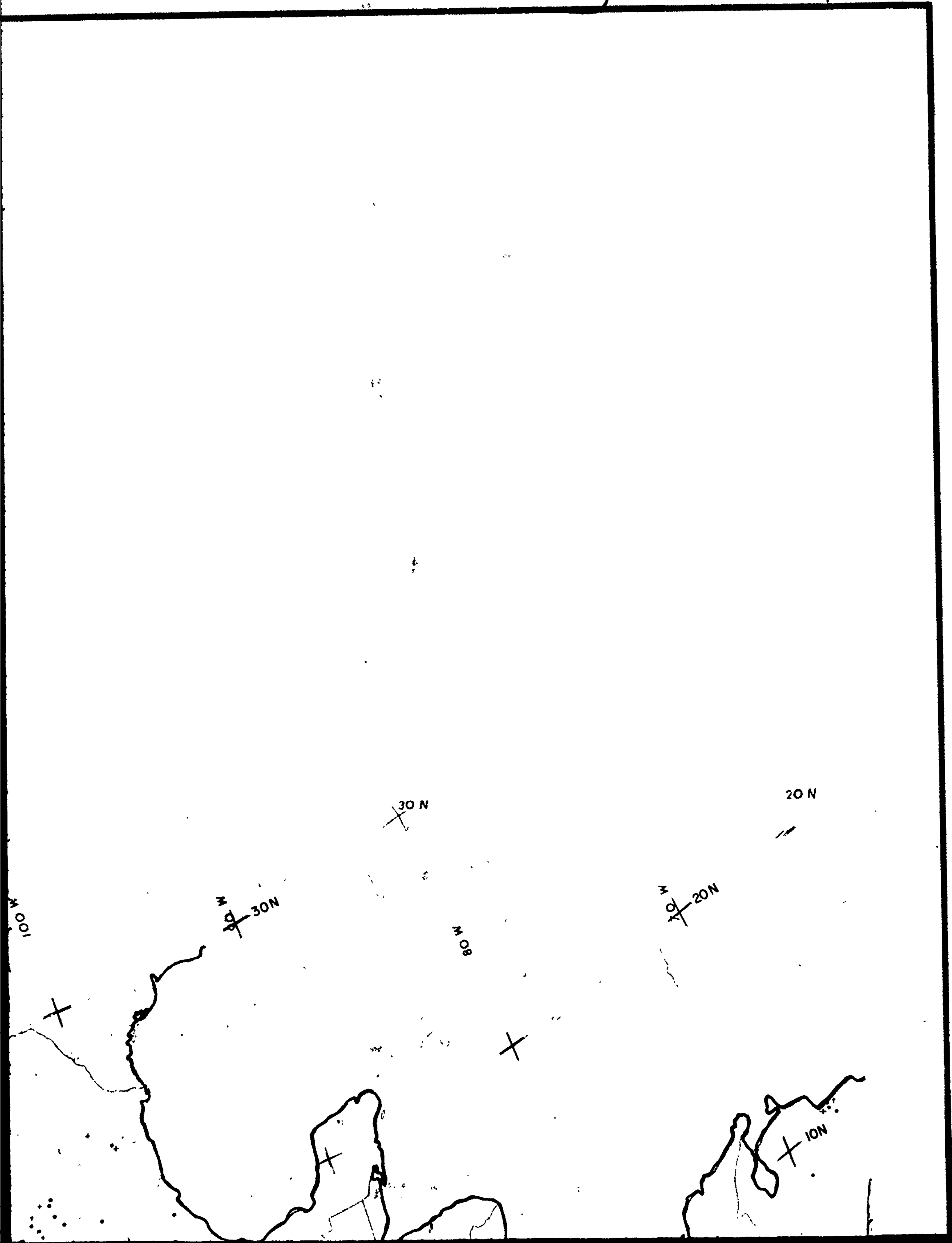
Northeastern Pacific Region

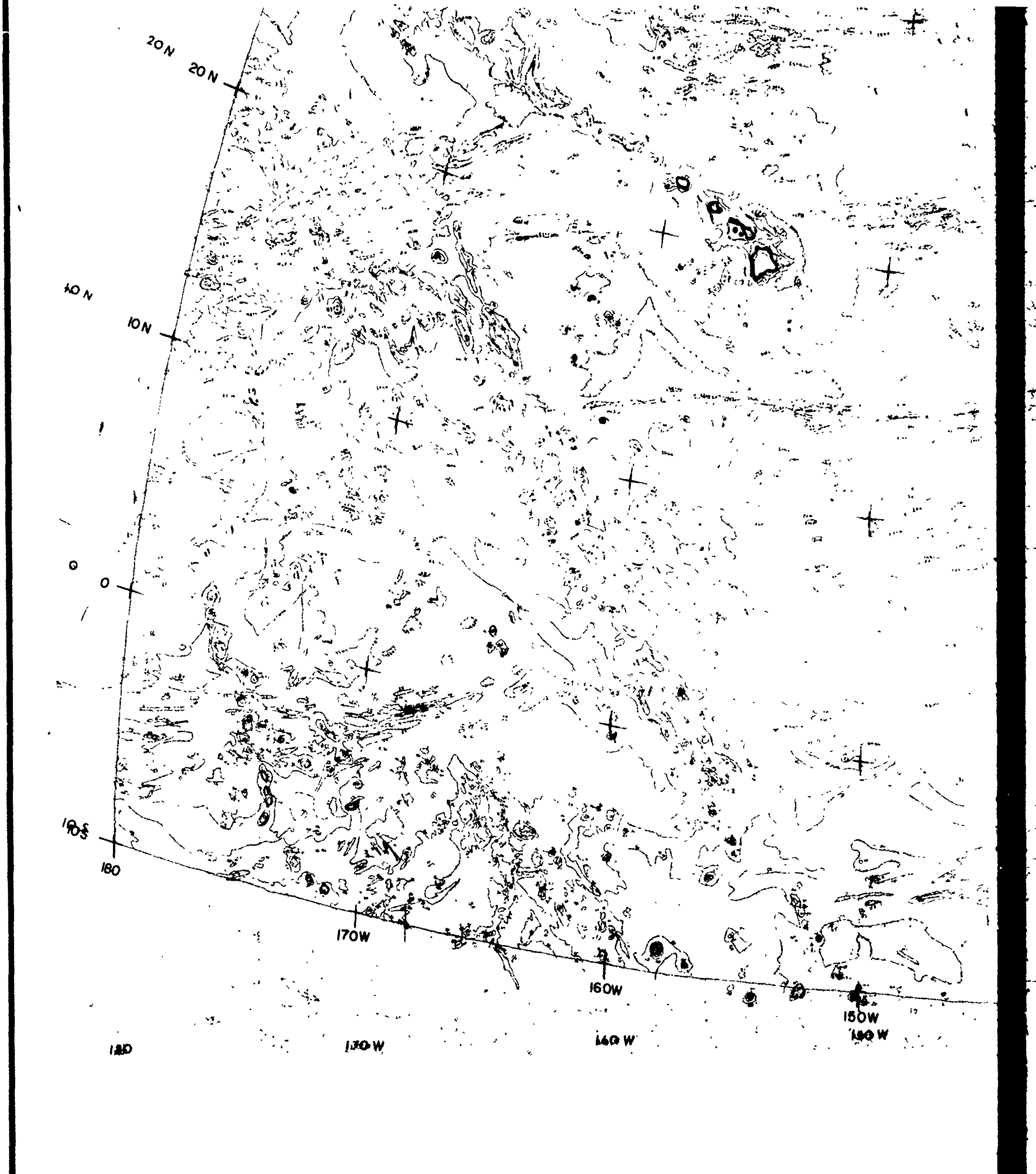
HEAT FLOW VALUES

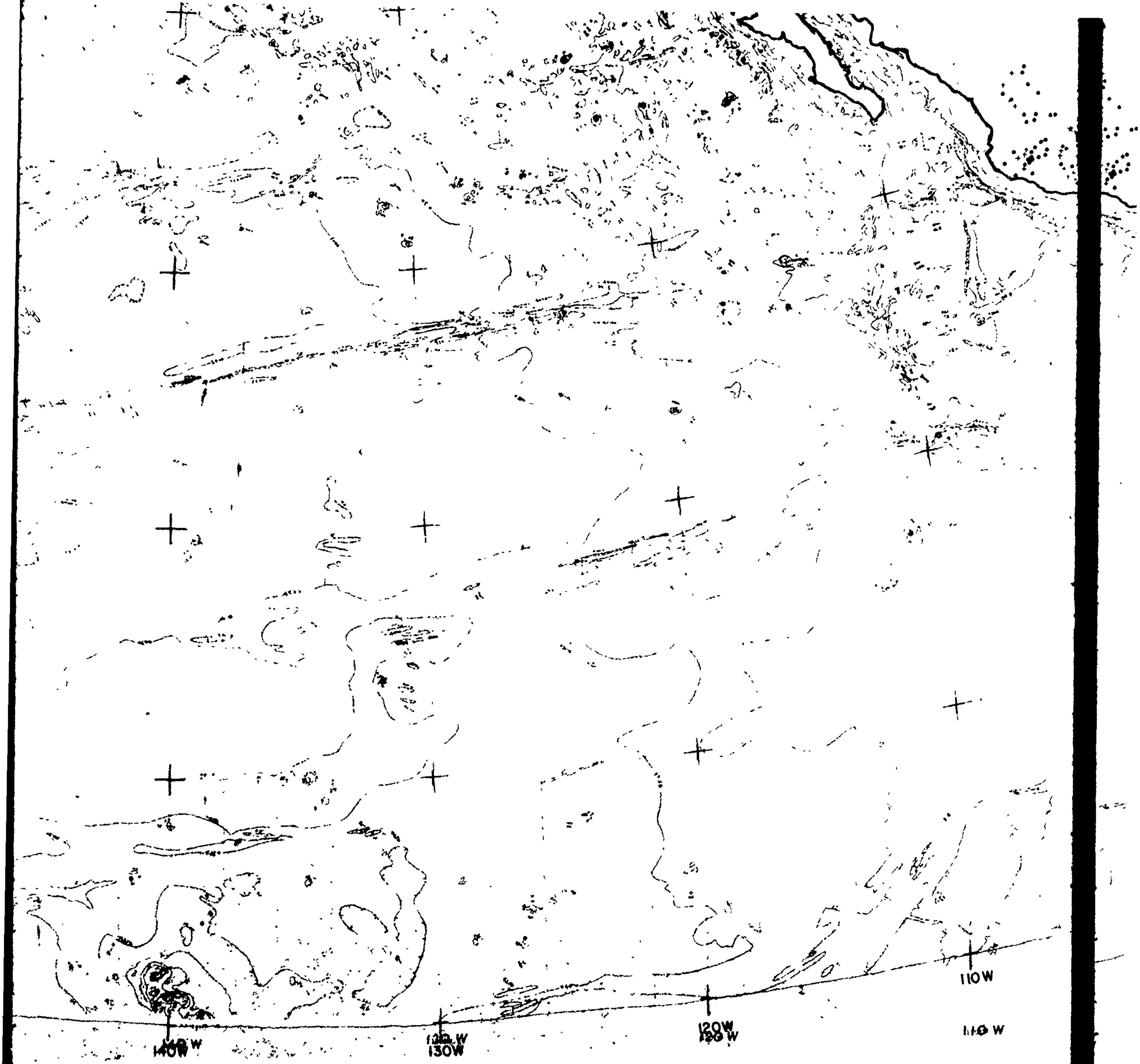
Plate IV


180
170
170W
60 N 60N
50 N 50N
40 N 40N
30 N 30N
20N 20N

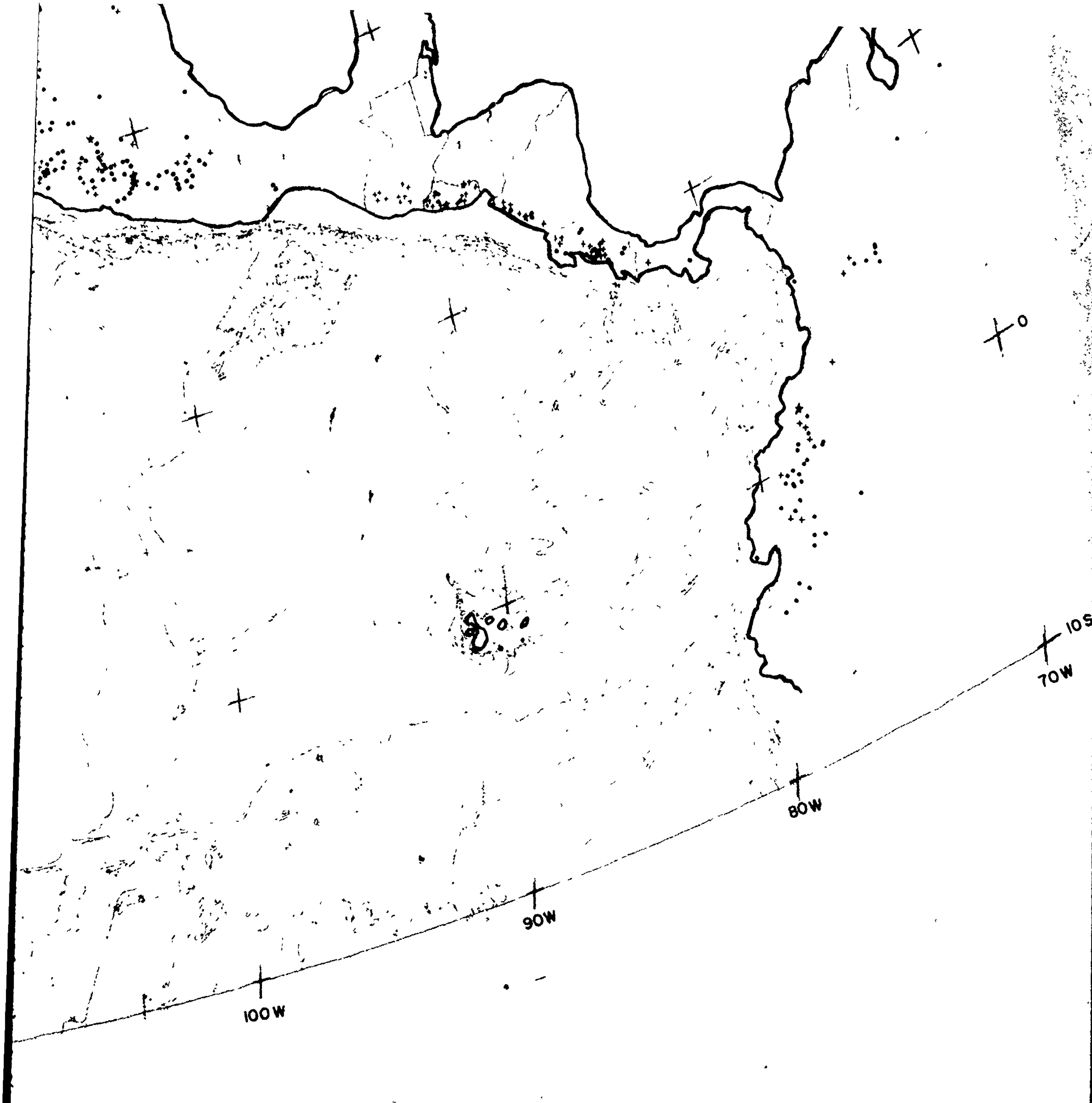
2


30 N
20 N
30N
20N
100 W
80 W
10N


20 N
20 N
10 N
10N
0
0
10S
180
170W
160W
150W
170 W
160 W
150 W



5



Northeastern Pacific Region

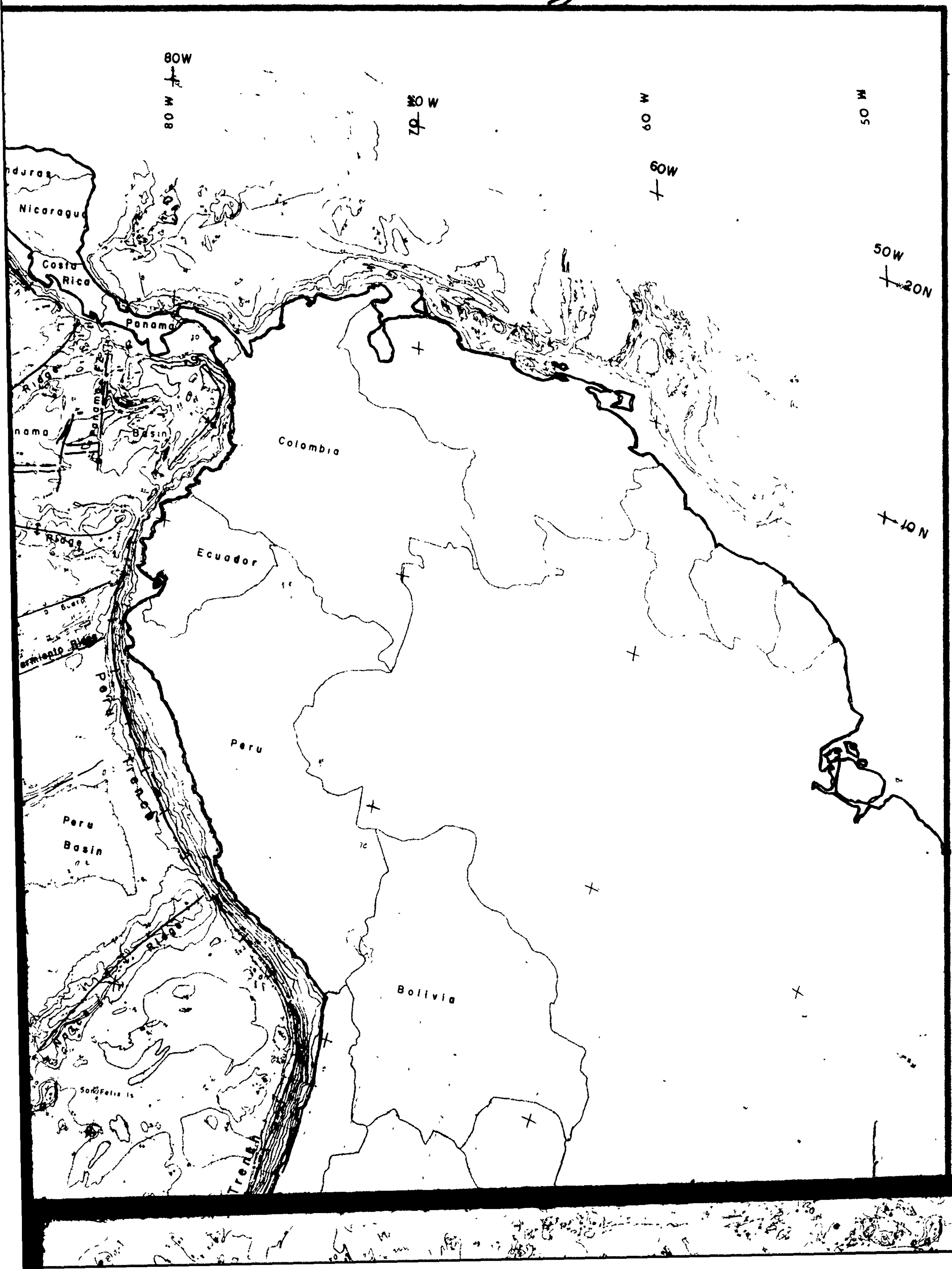
THERMAL SPRINGS

Plate V

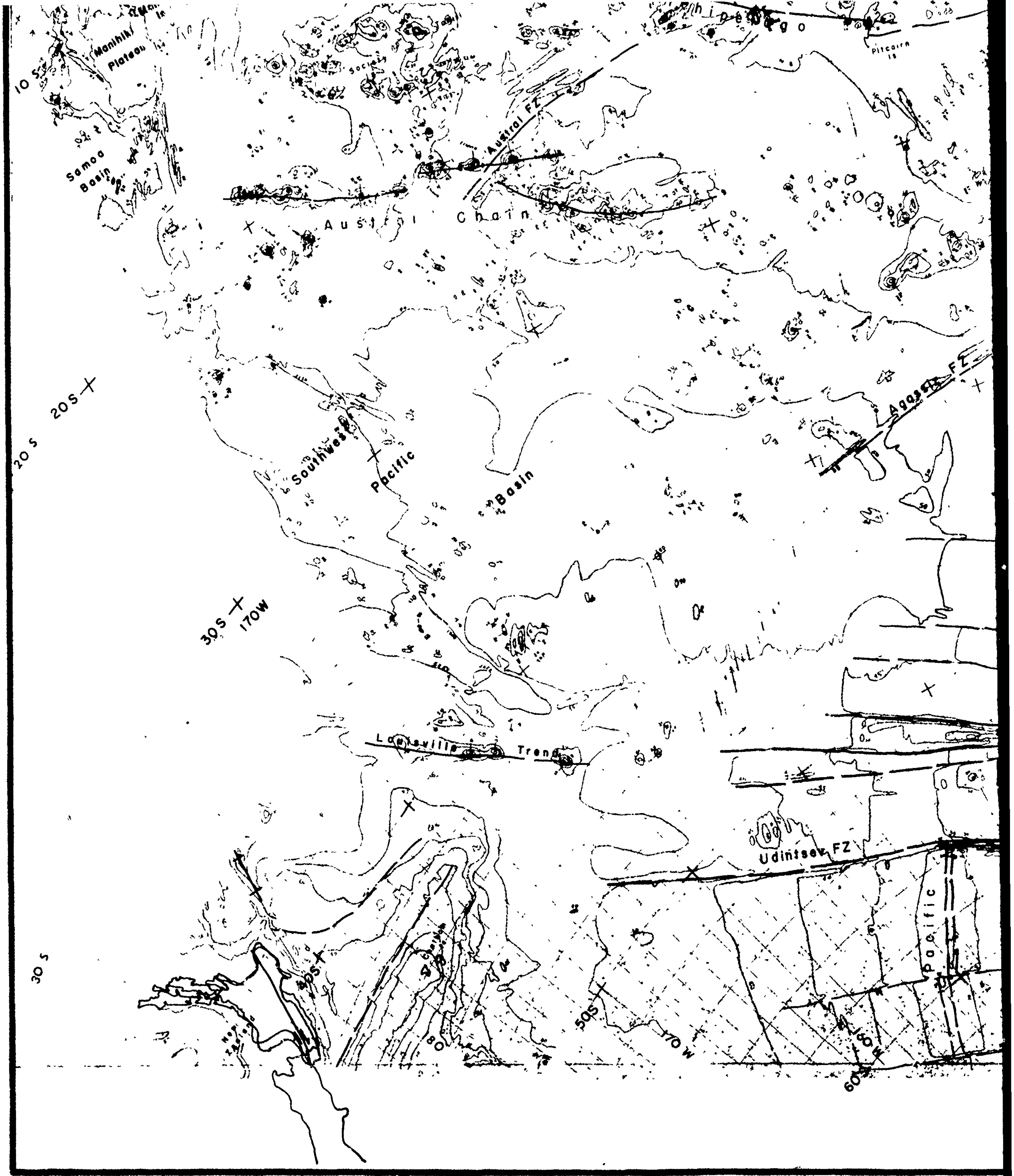
160 W
150 W
140 W
130 W
30 N
140W
150W
Hawaii
20 N
160 W
Clarion FZ
Clipperton Fracture Zone
Galapagos Fracture Zone
10 N
Line
Christmas Is.
Marquesas Is.
Fracture Zone
Tuamoto FZ
Ridge
Marquesas
Penrhyn Basin
Manihiki Is.
Manihiki Plateau
Society
Pitcairn Is.

2

120W
110W
100W
90W
Mexico
Guatemala
Honduras
El Salva.
Nicaragua
Costa Rica
Middle America Trench
Guatemala Basin
Siqueiros FZ
Galapagos Rift
Cocos Ridge
Panama
Carnegie Ridge
Sarmiento Ridge
Bauer Basin
East Pacific Rise
Peru Basin
Quiros FZ
Easter Island FZ



80W
70W
60W
50W
20N
10N
Nicaragua
Costa Rica
Panama
Basin
Colombia
Ecuador
Ridge
Peru
Peru Trench
Peru Basin
Bolivia
Trench

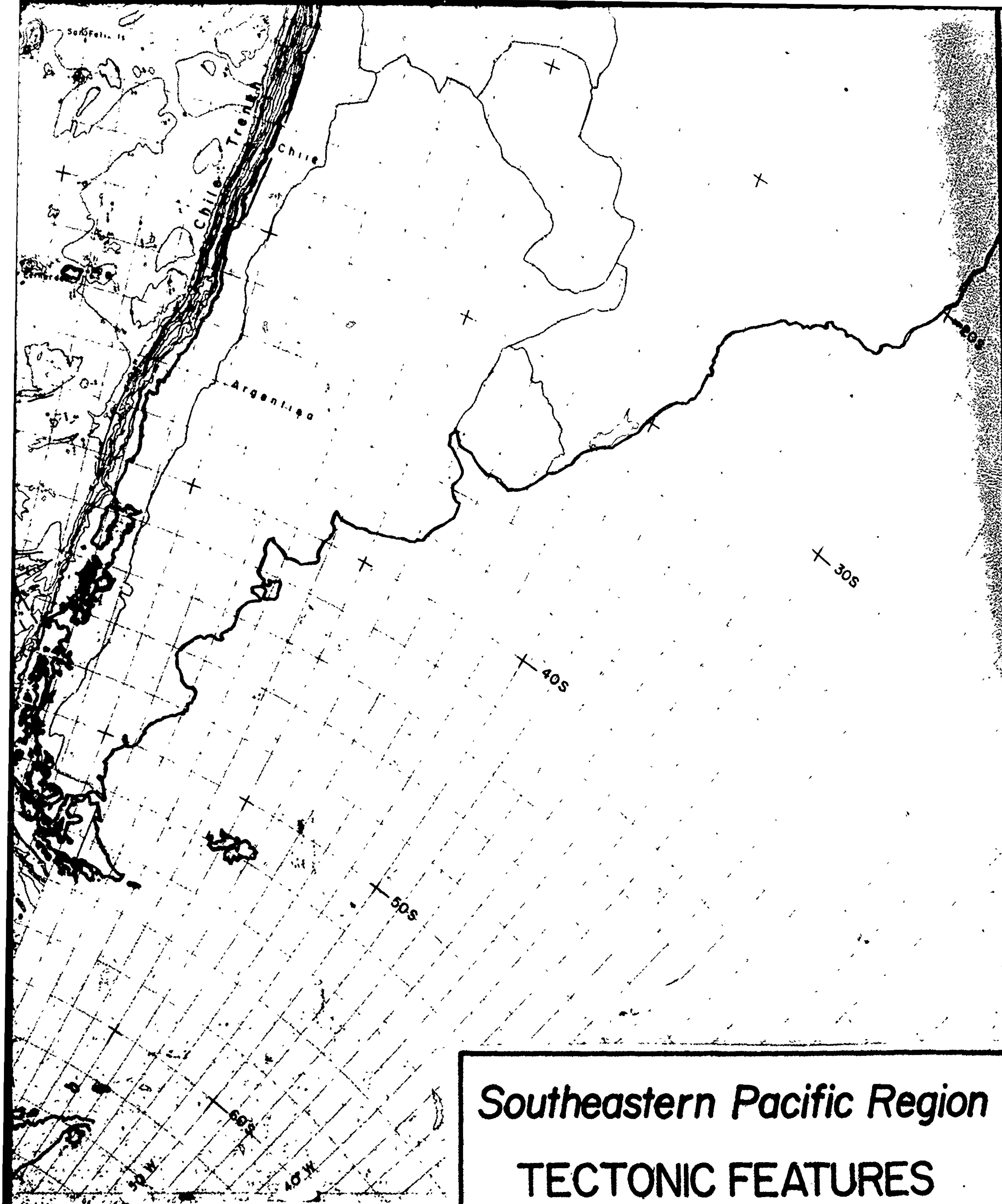


Manihiki Plateau
Samoa Basin
Austral FZ
Austral Chain
Pitcairn Is
Agassiz FZ
Southwest Pacific Basin
Louisville Trend
Udintsev FZ
Pacific
10 S
20 S
20 S
30 S
170W
30 S
50S
170W
60

4


Chile FZ
Challenger FZ
Chile
Ridge
FZ
Fernandez
Antarctic
Ridge
FZ
Menard FZ
Humboldt
Plain
Eltanin
Southeast
Pacific
Basin
Bellingshausen
Plain
100 W
110W
120W
130W
140W
90W
80W

5



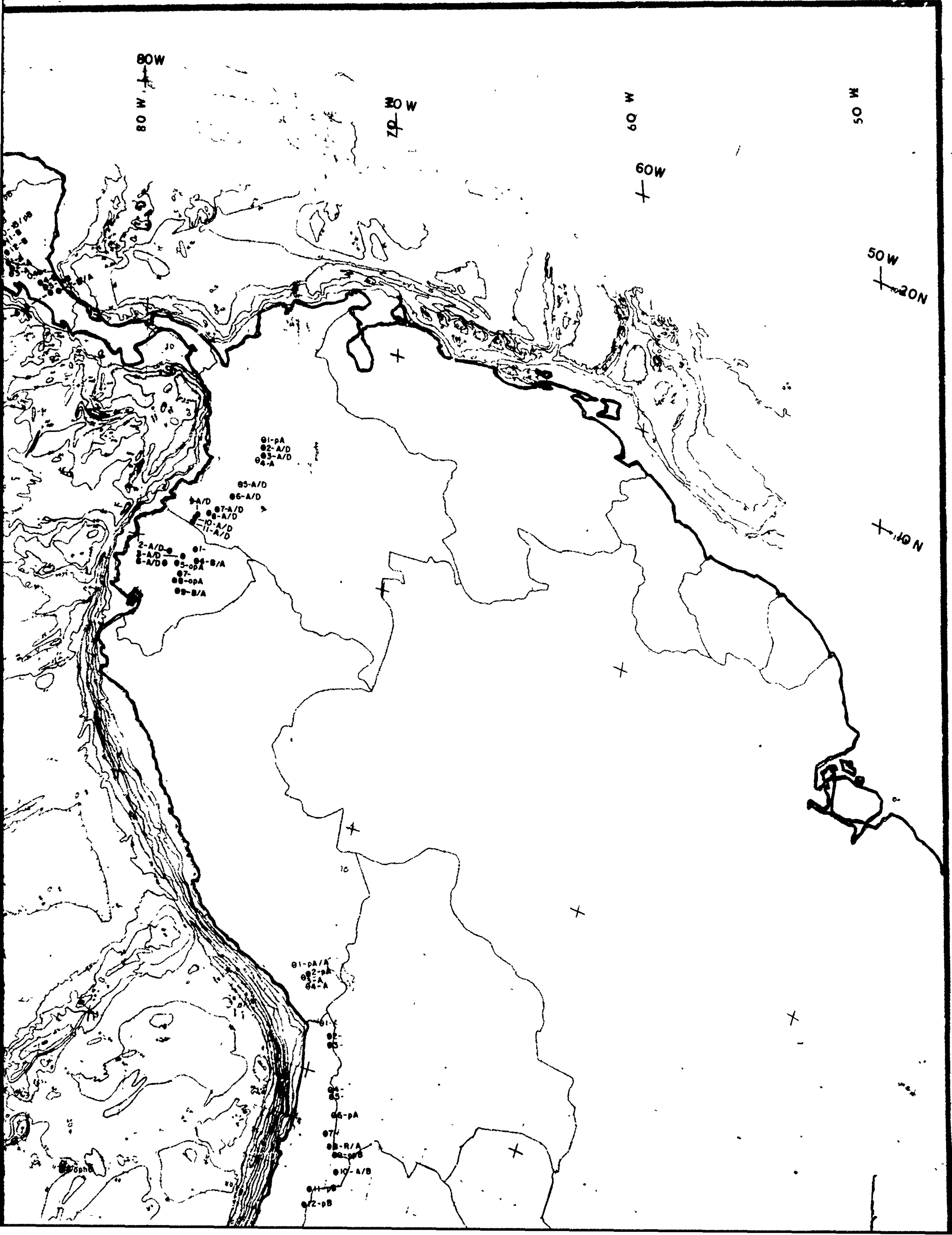
Southeastern Pacific Region
TECTONIC FEATURES
Plate VI

/

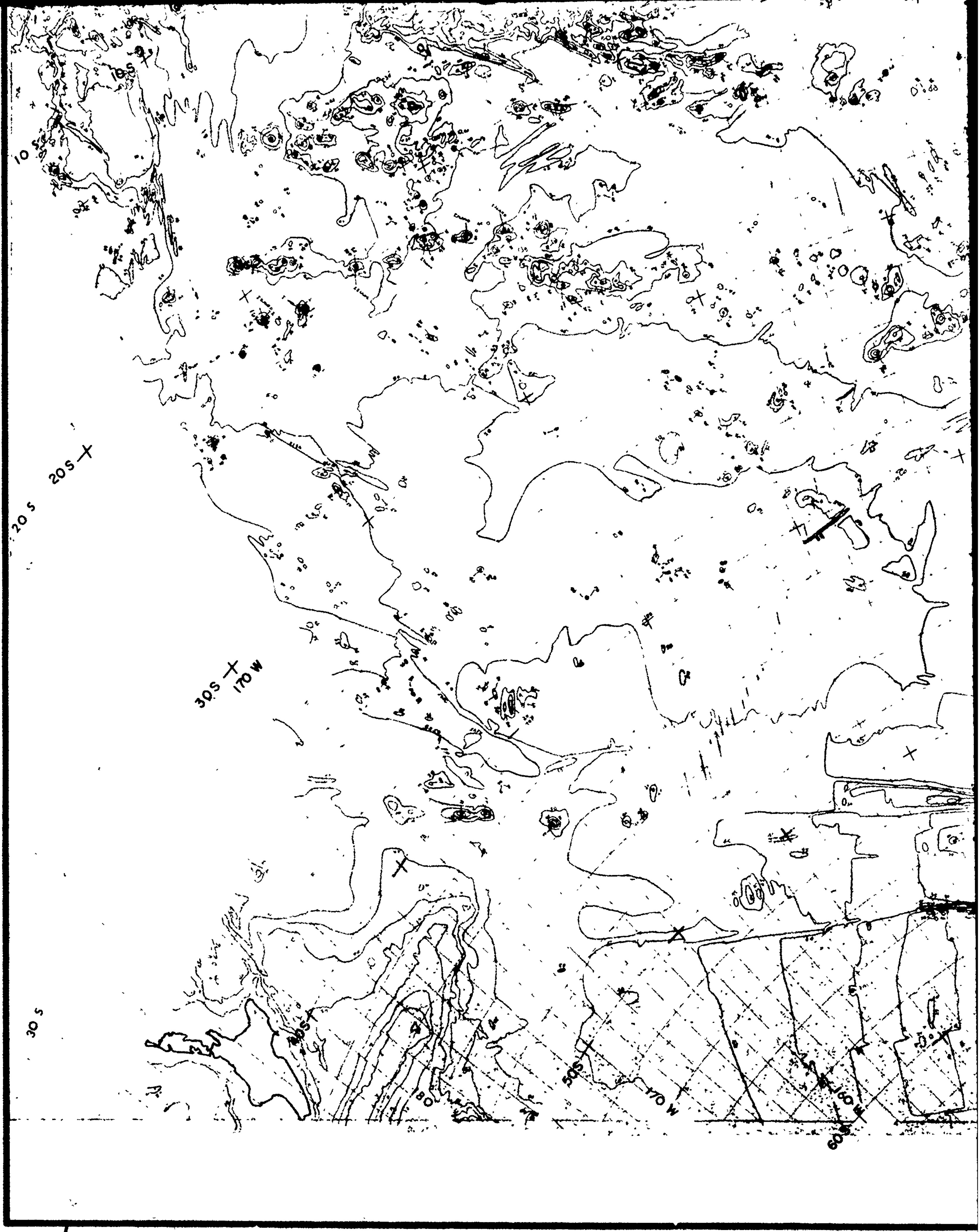
160 W
150 W
140 W
130 W
30 N
140W
150W
20 N
160W
10 N
10 S

2

3

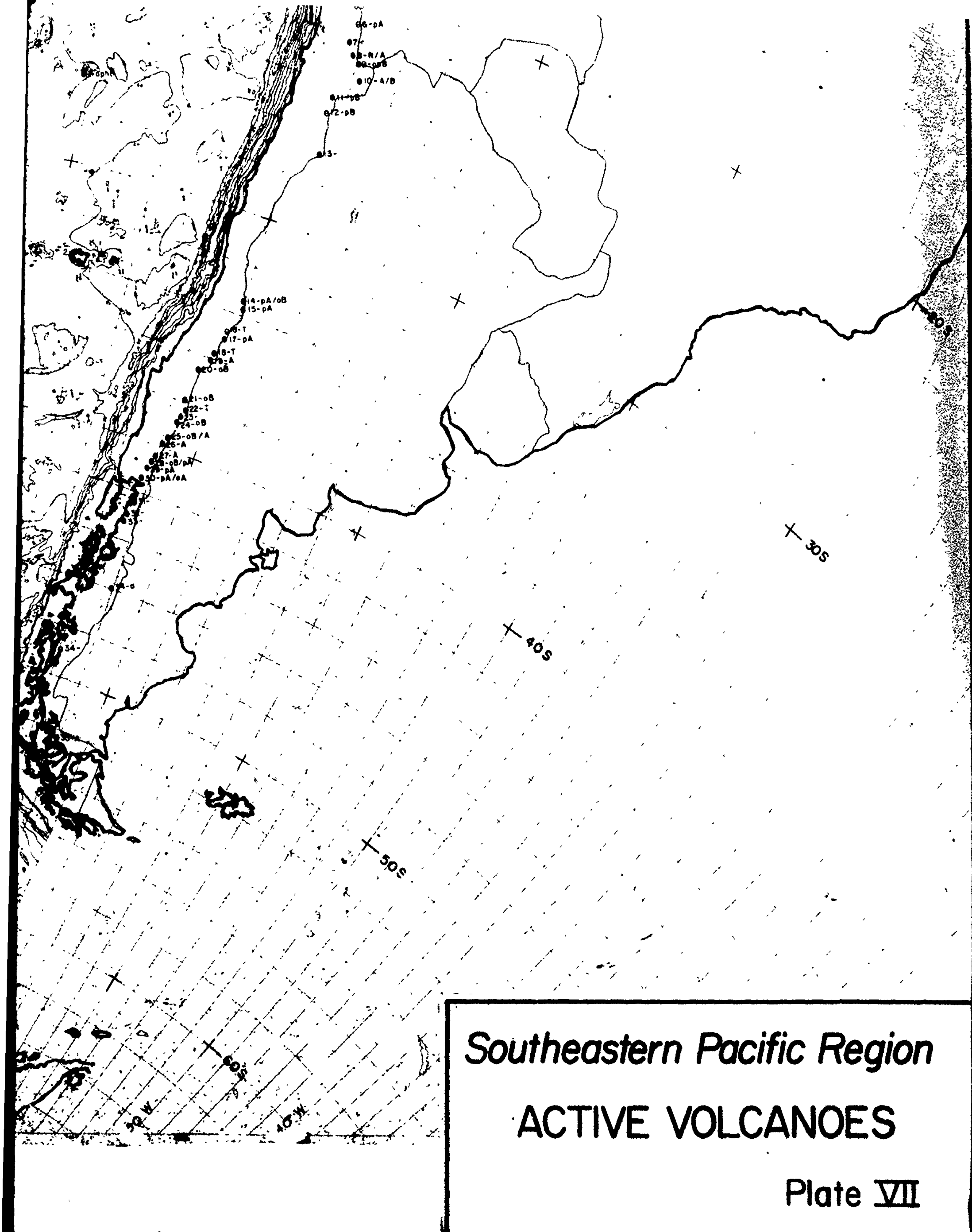


80W
70 W
60W
50W
20N
10N
1-pA
2-A/D
3-A/D
4-A
5-A/D
6-A/D
7-A/D
8-A/D
10-A/D
11-A/D
4-B/A
5-opA
8-opA
9-B/A
1-pA/A
2-pA
3-A
4-A
6-pA
8-R/A
9-pB
10-A/B
11-pB
12-pB



4

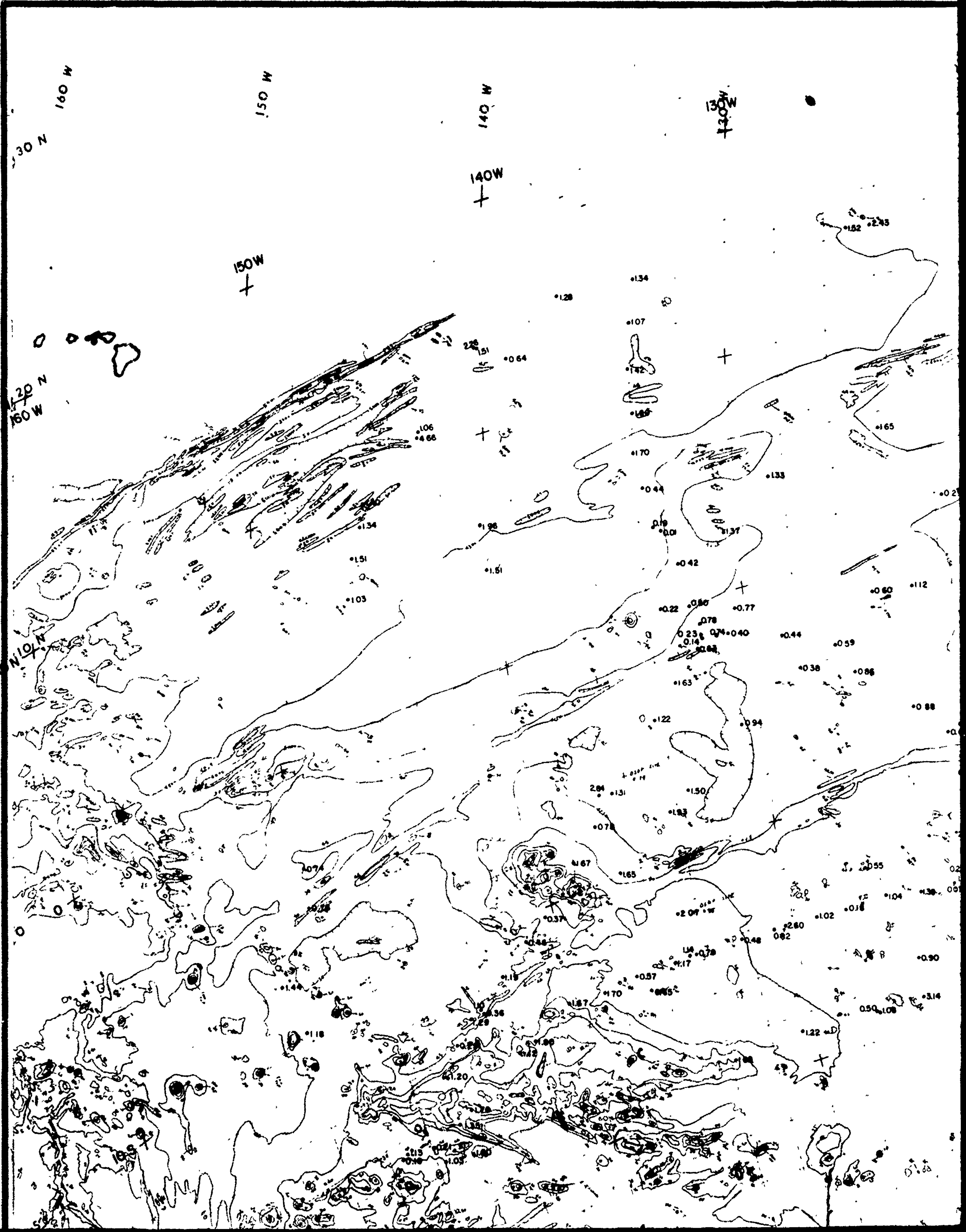

100 W
110W
120W
150 W



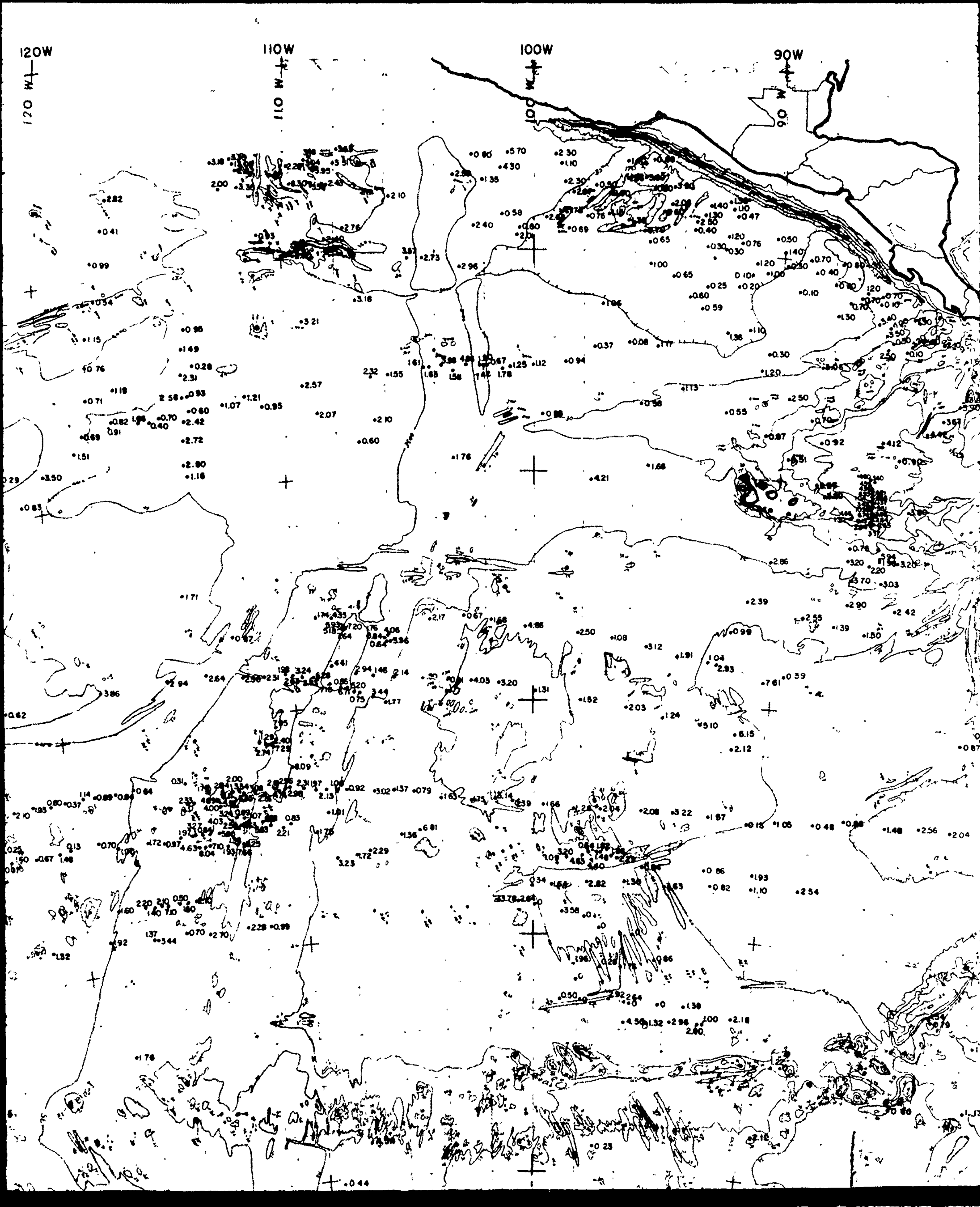
Southeastern Pacific Region

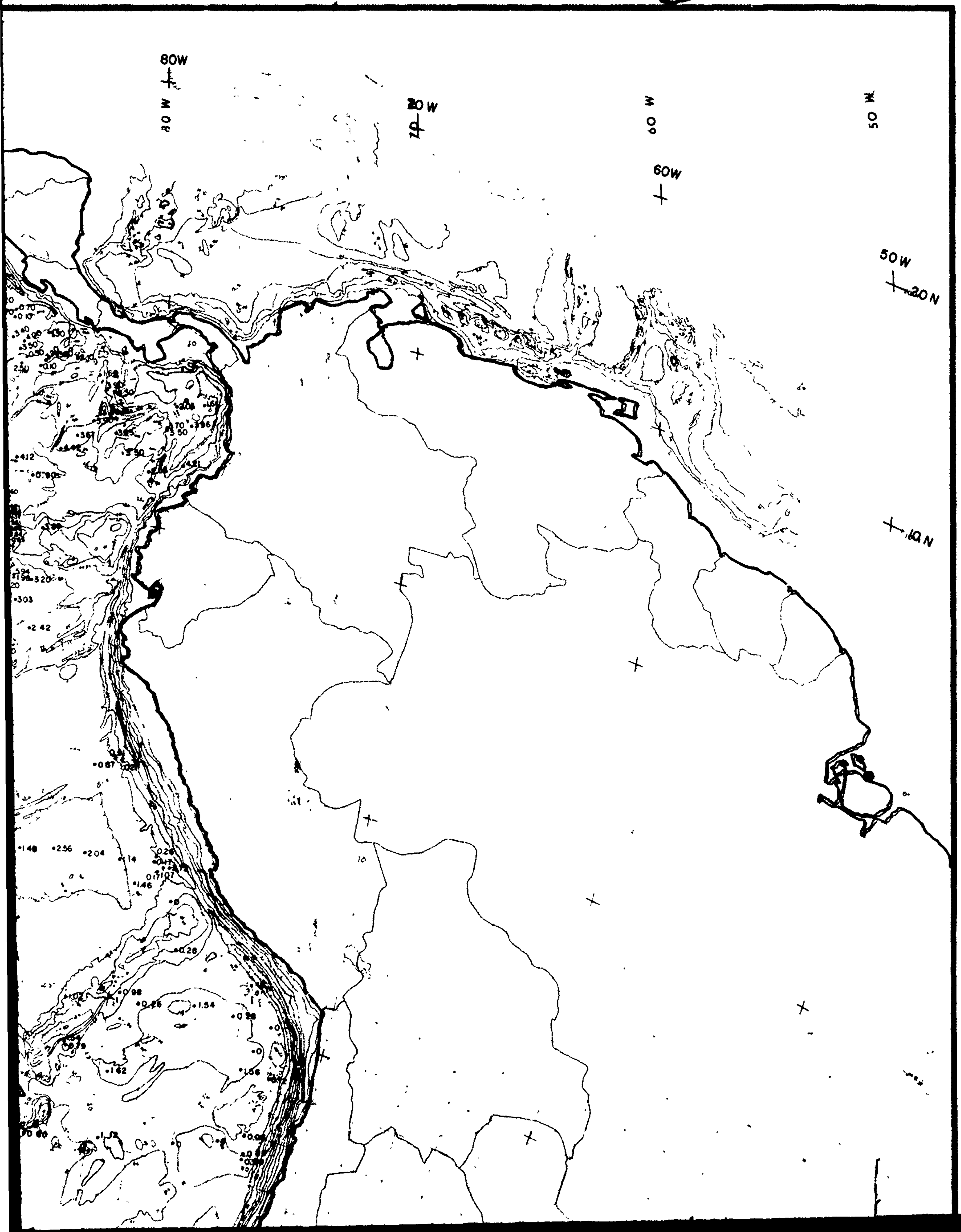
ACTIVE VOLCANOES

Plate VII

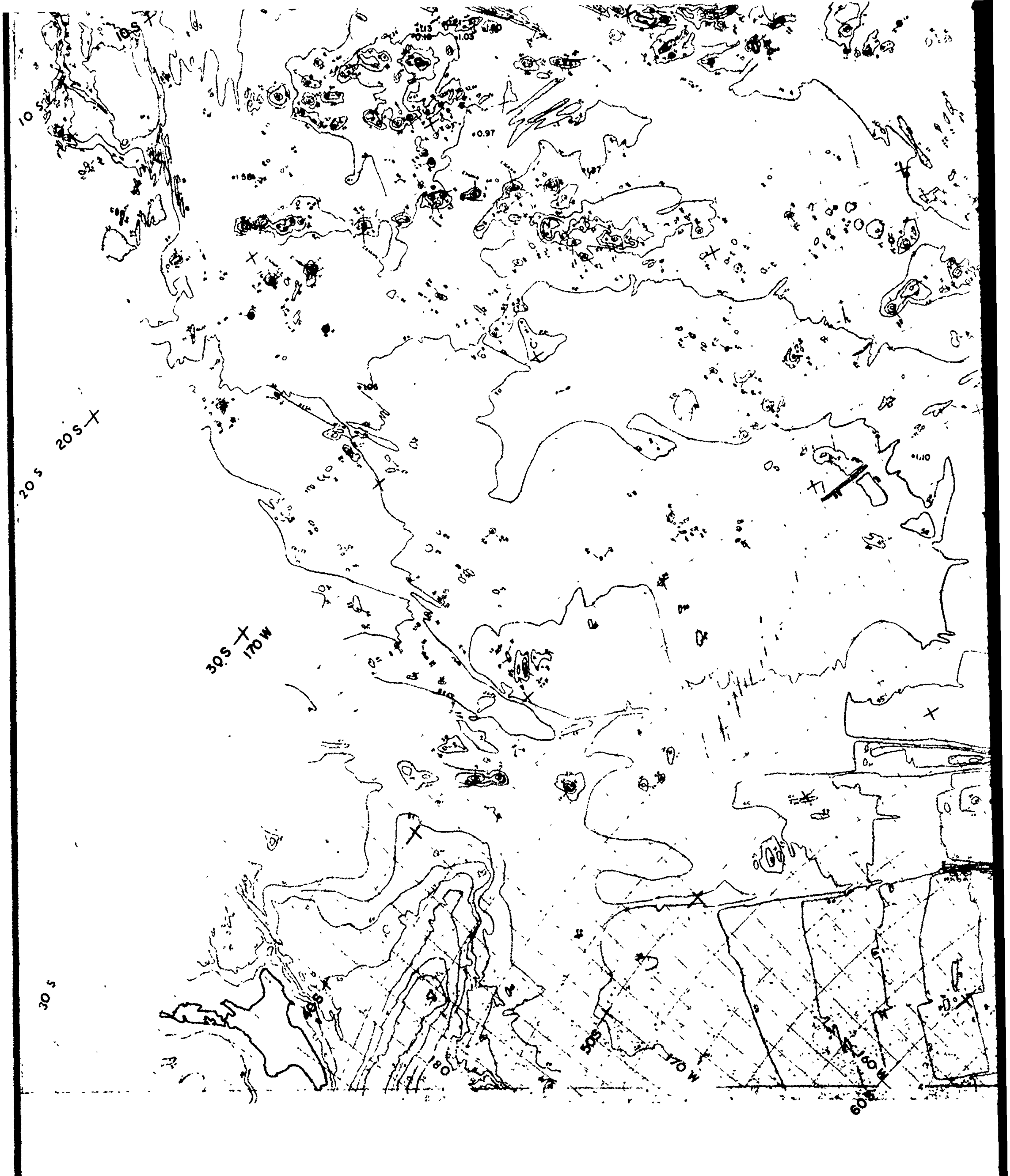

160 W
150 W
140 W
130 W
30 N
140W
150W
20 N
160W
10 N

2

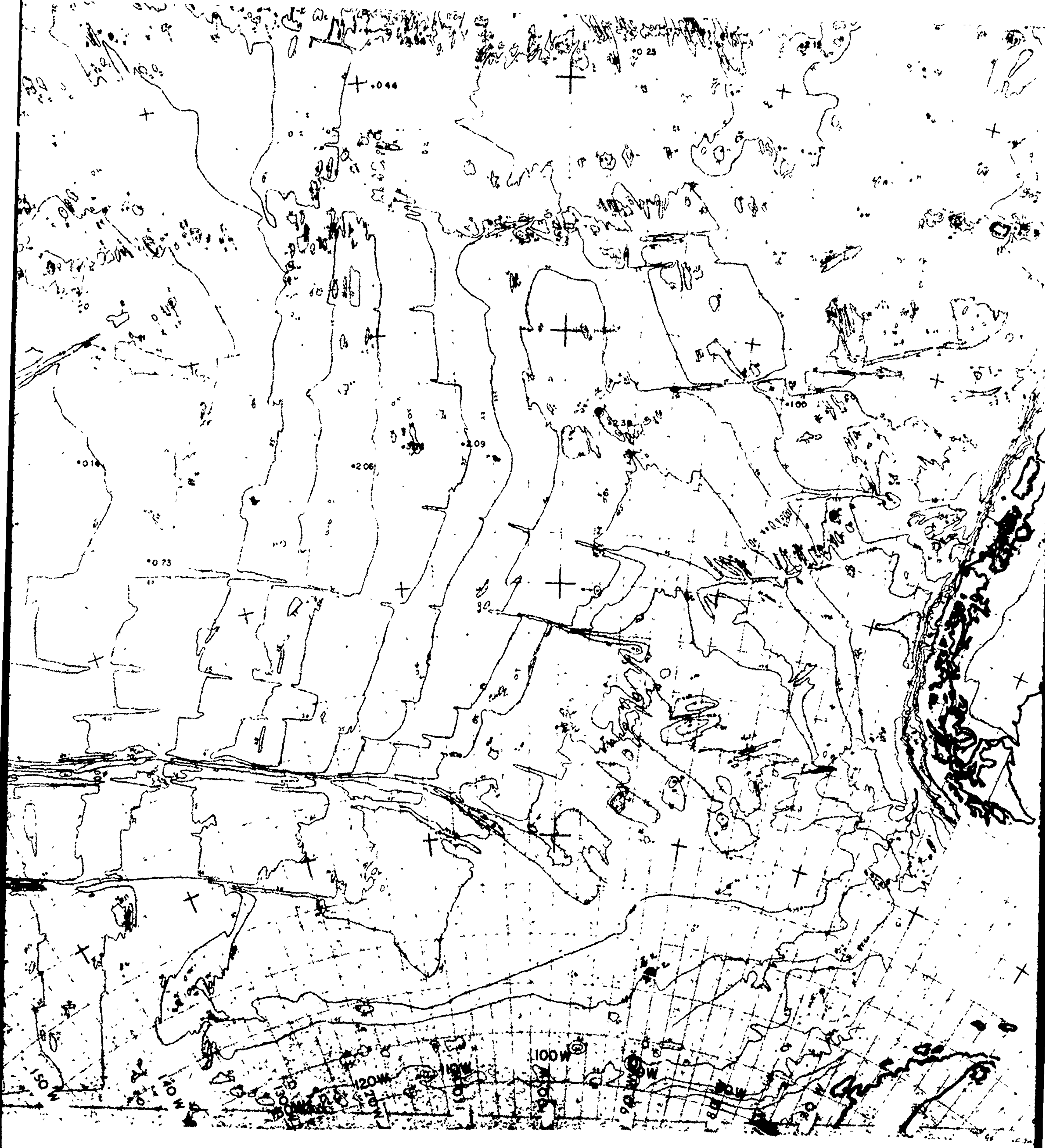




80W
70 W
60W
50W
20N
10N

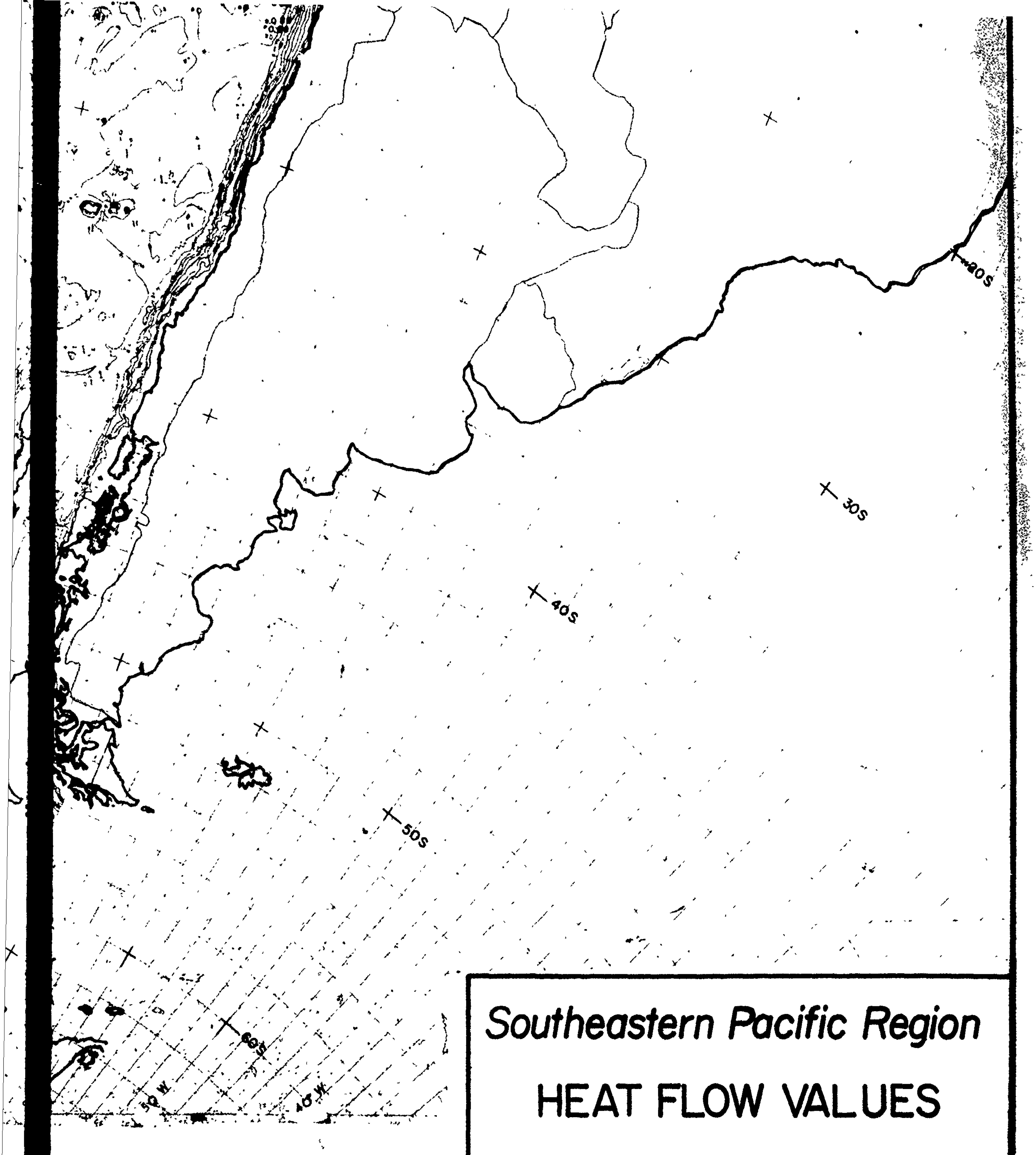


4



5

1



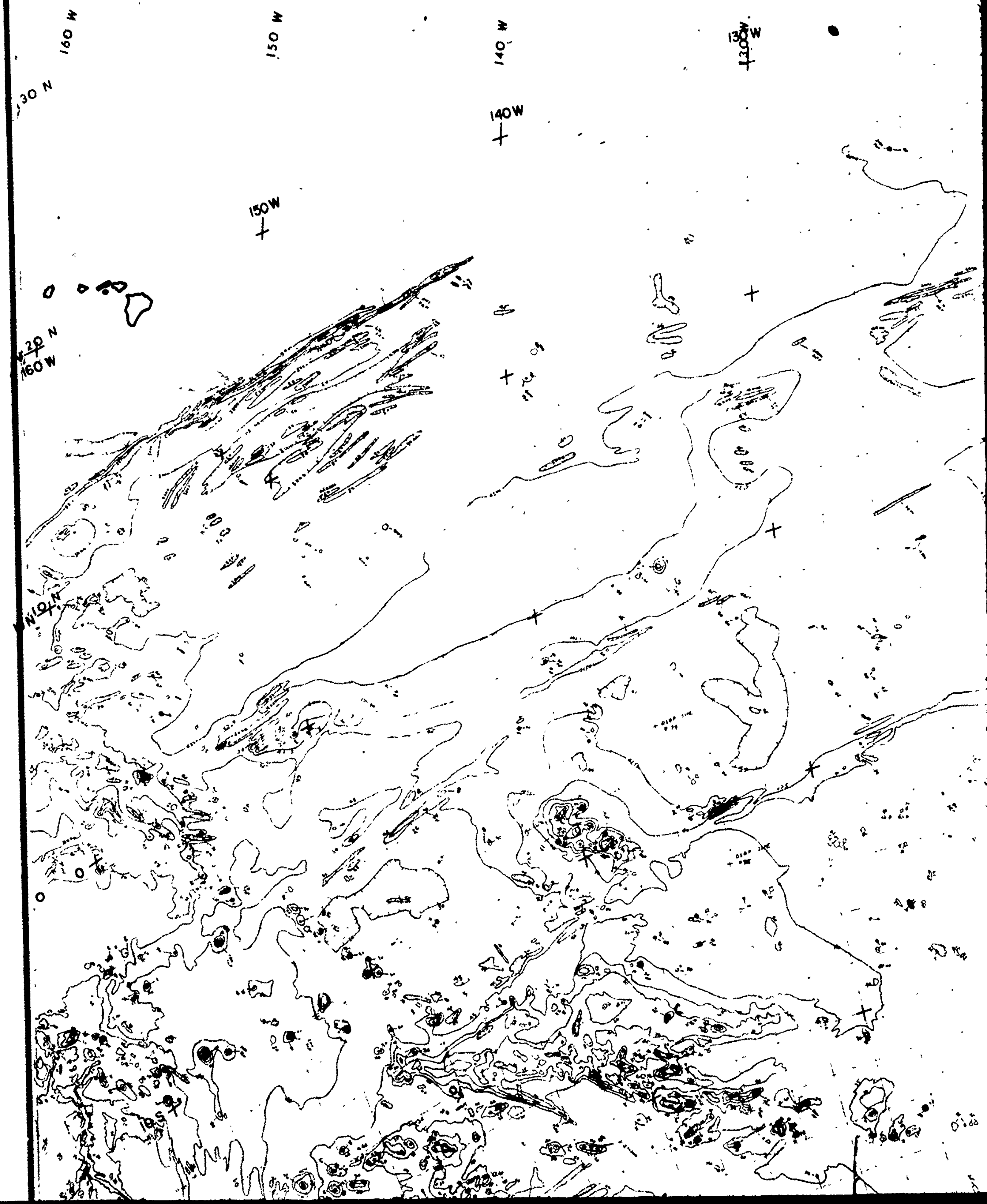
Southeastern Pacific Region

HEAT FLOW VALUES

Plate VIII

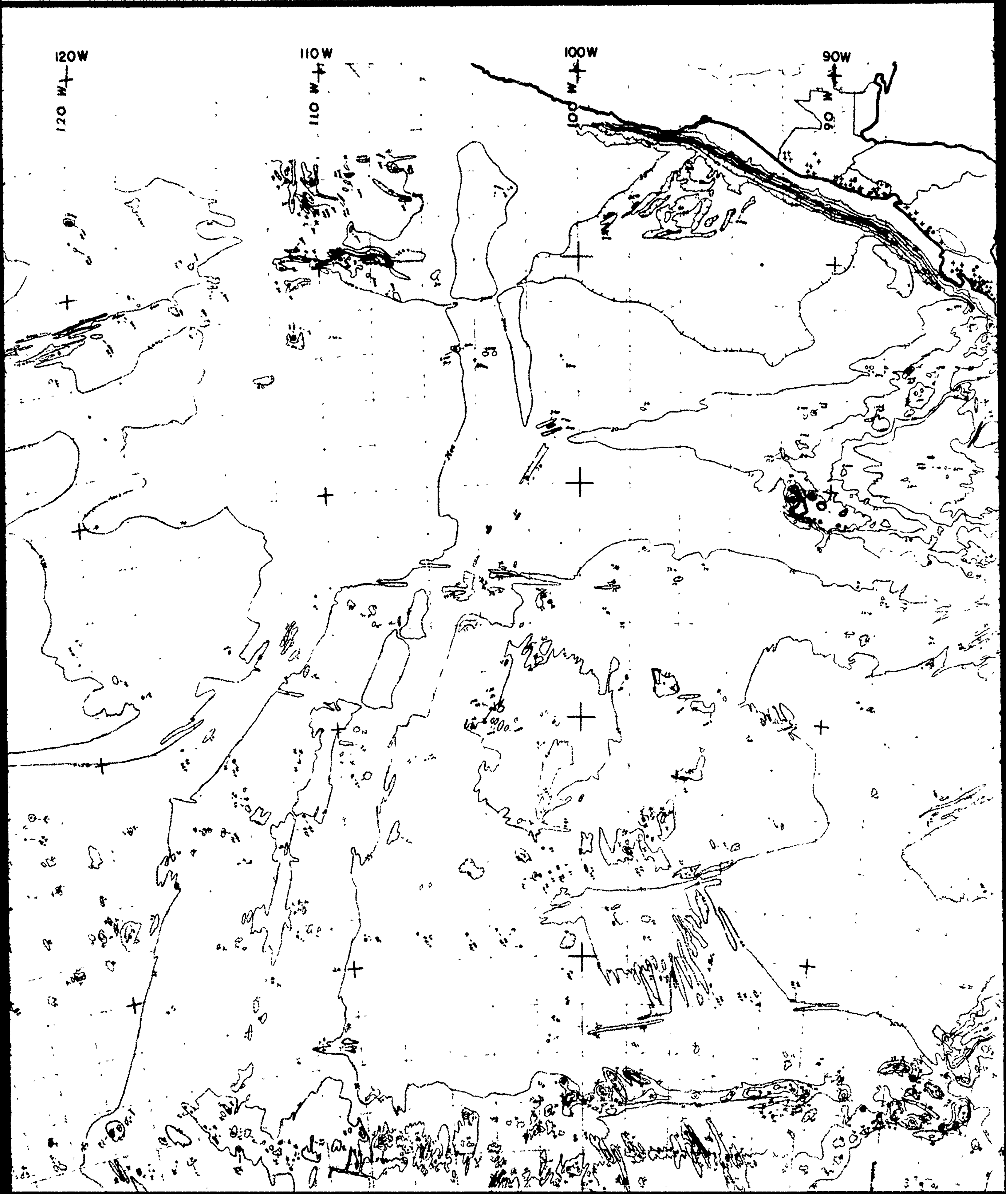
6

2

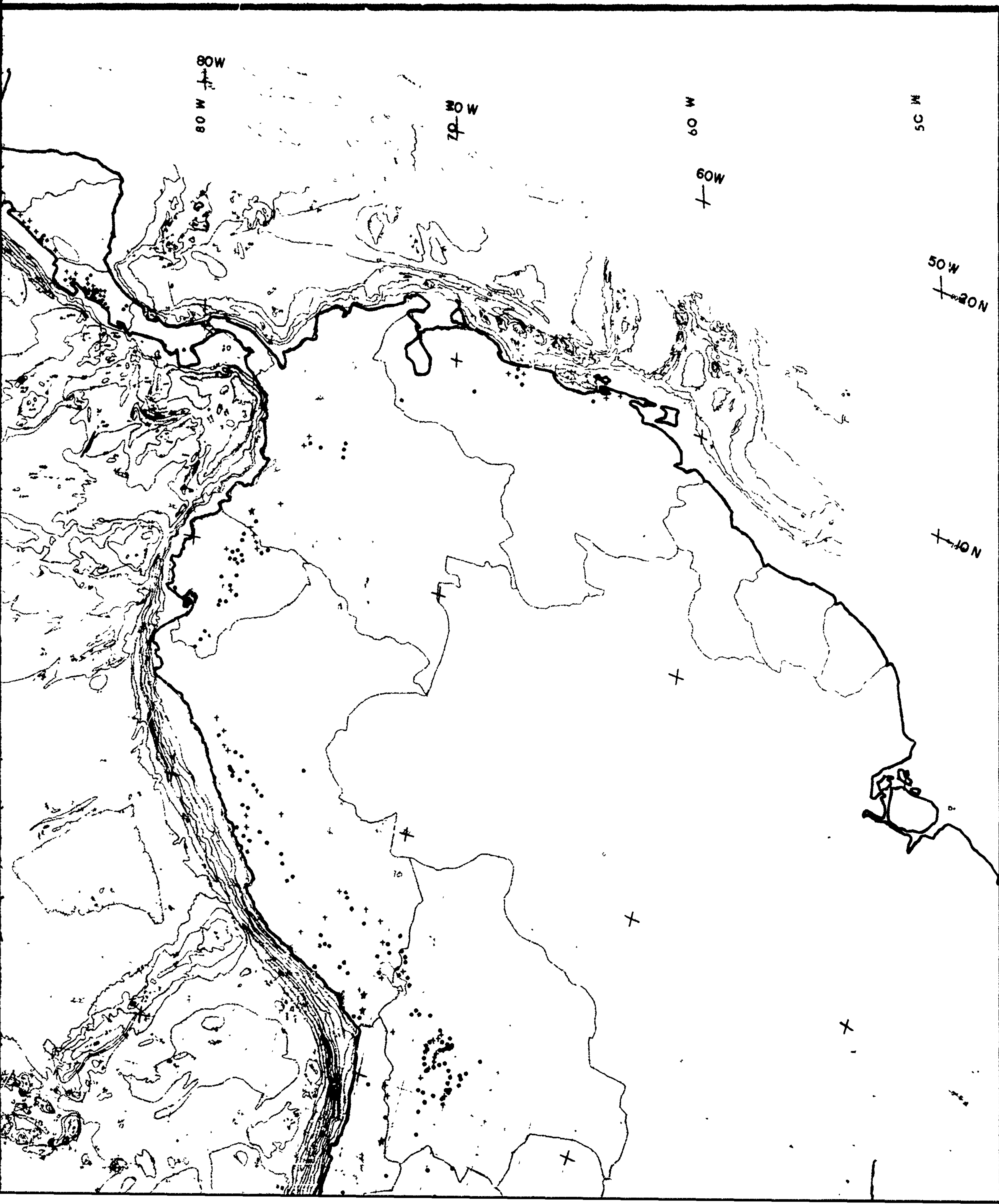


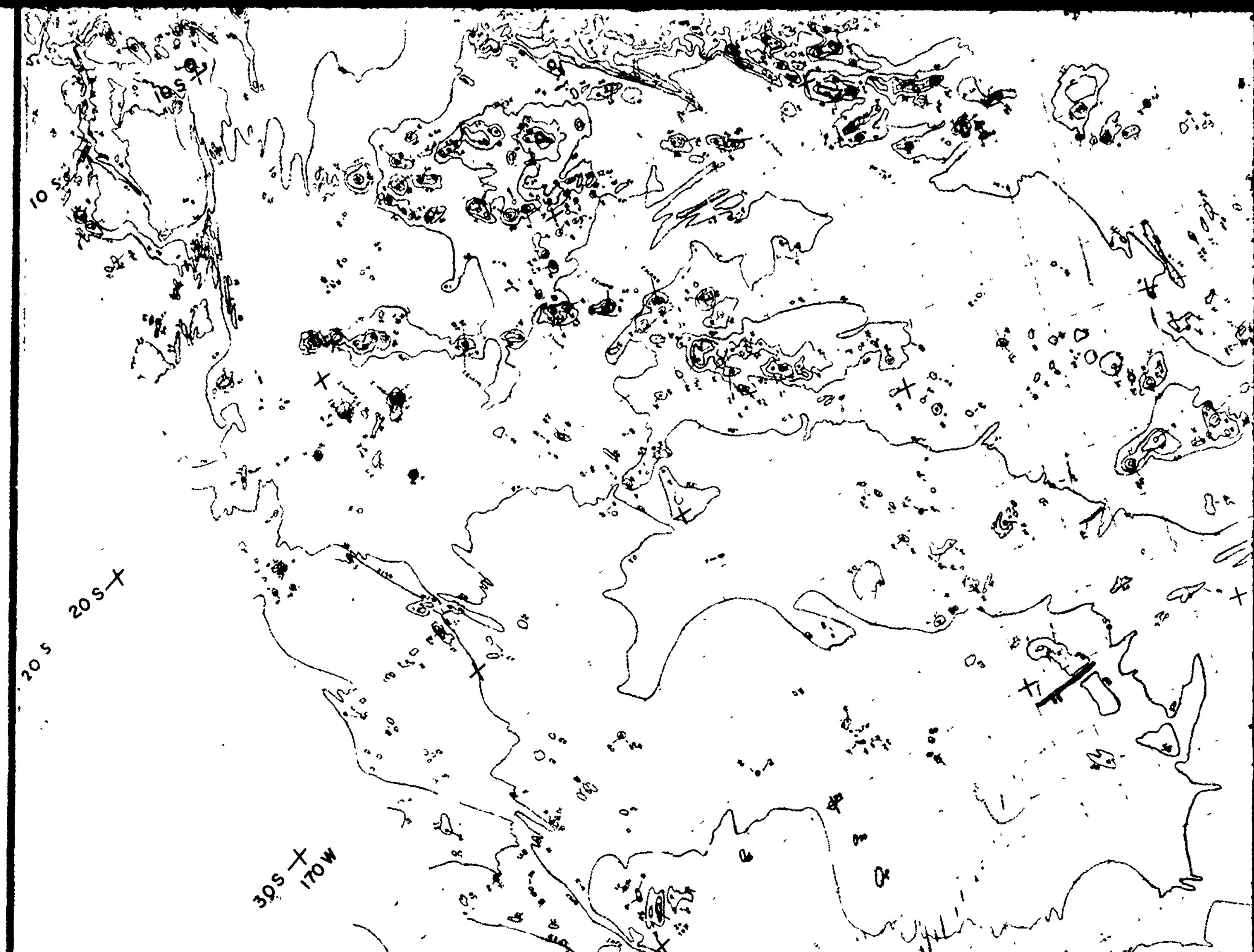
3

2

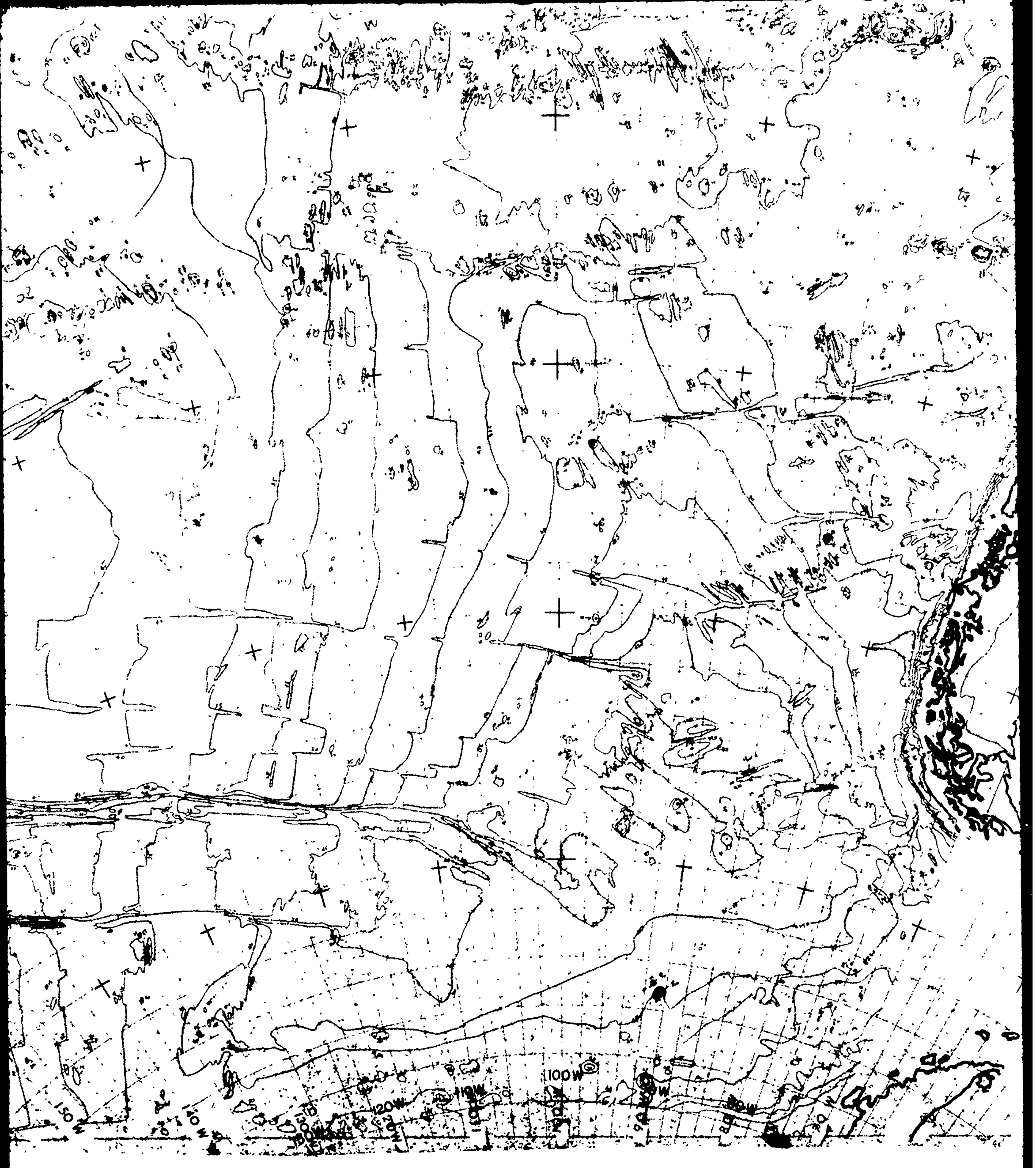


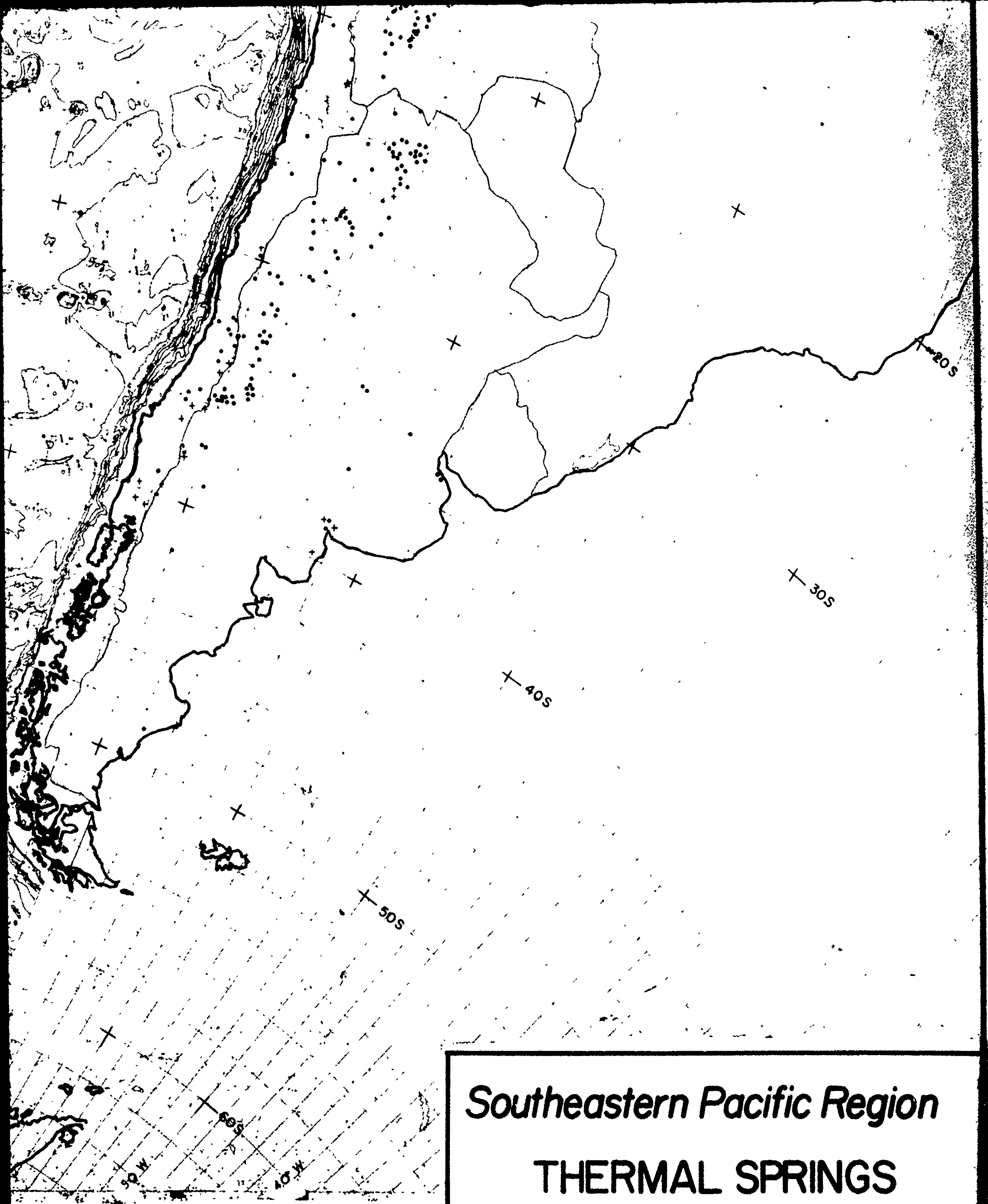
3





4

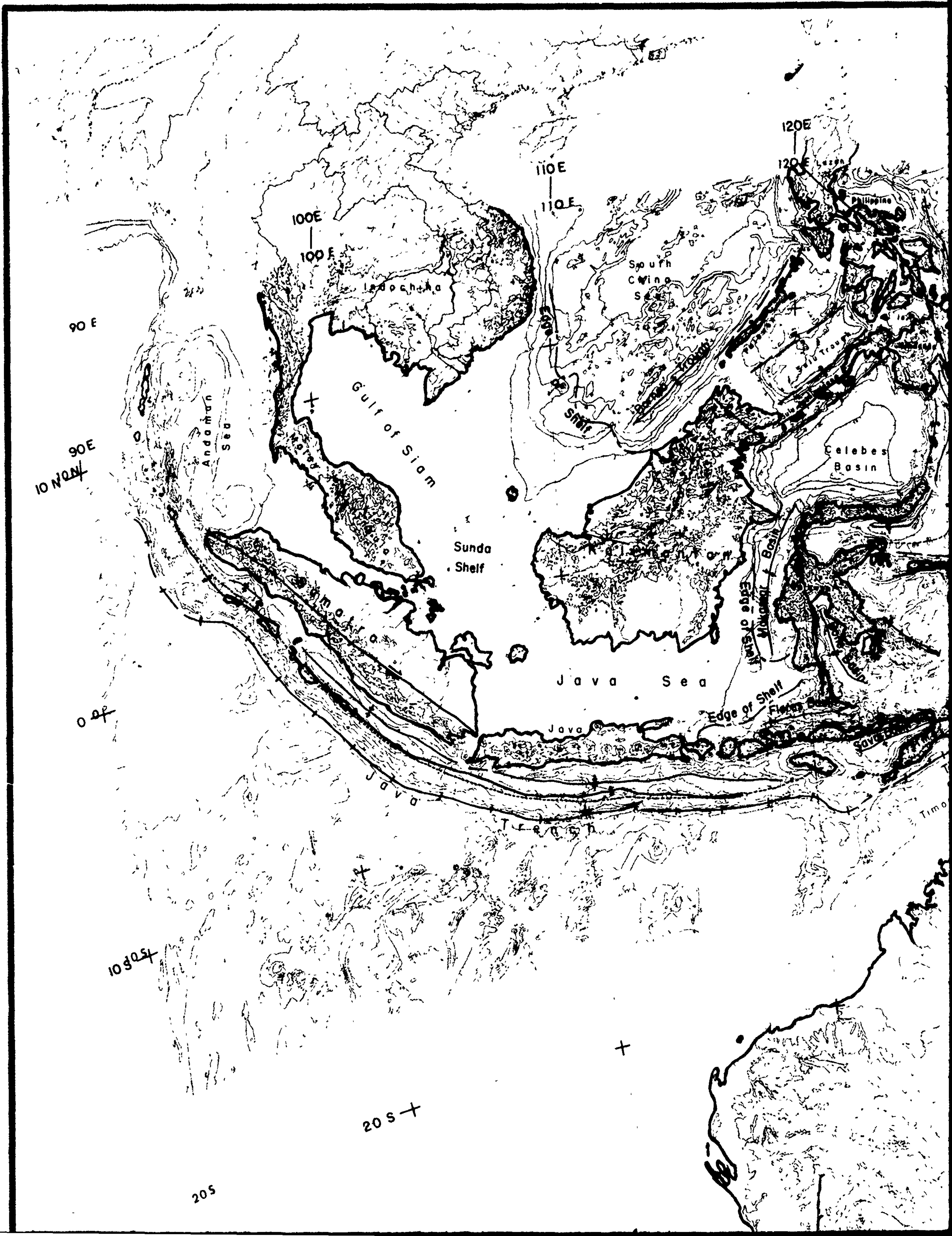

150W
120W
110W
100W



Southeastern Pacific Region

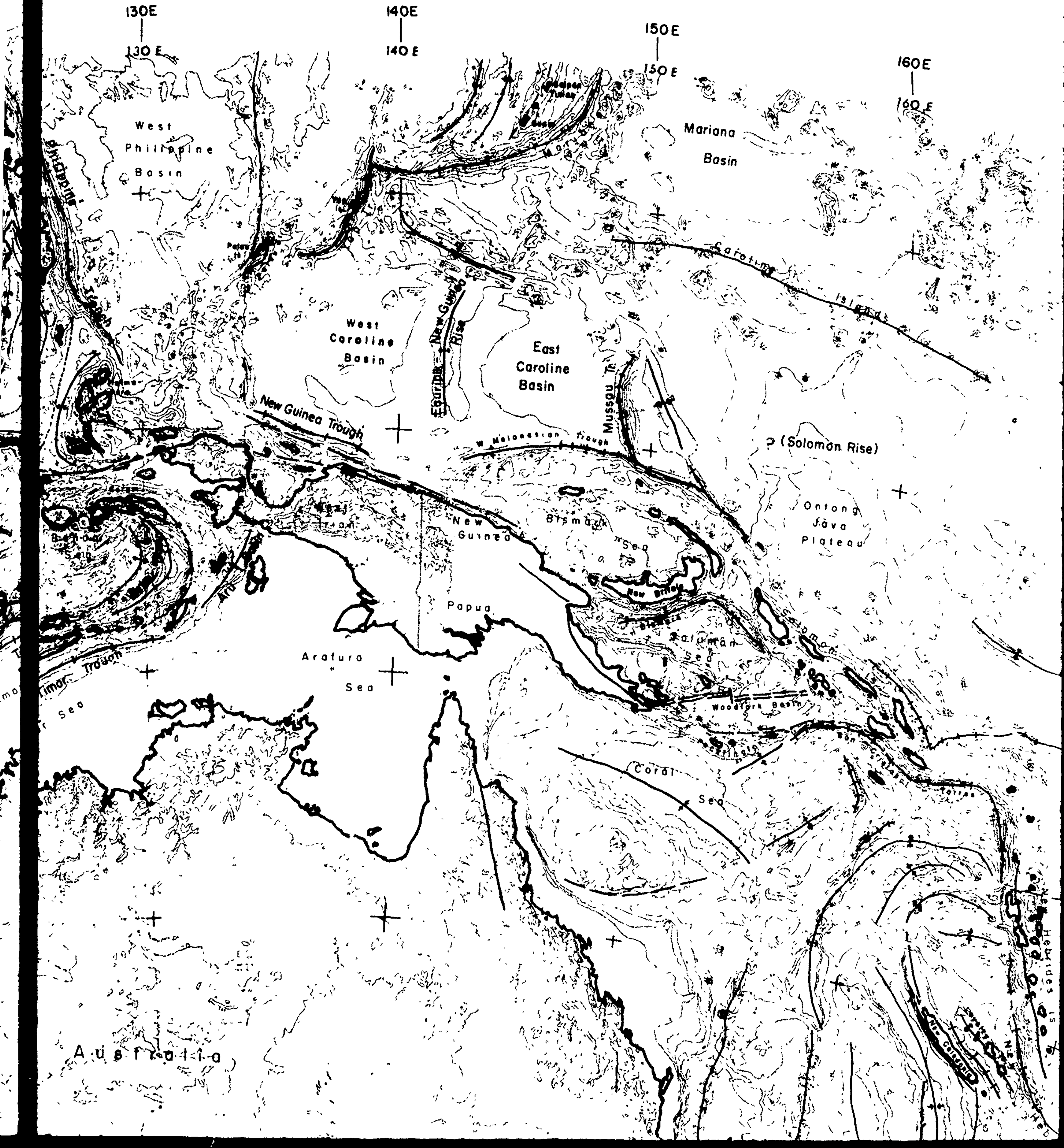
THERMAL SPRINGS

Plate IX

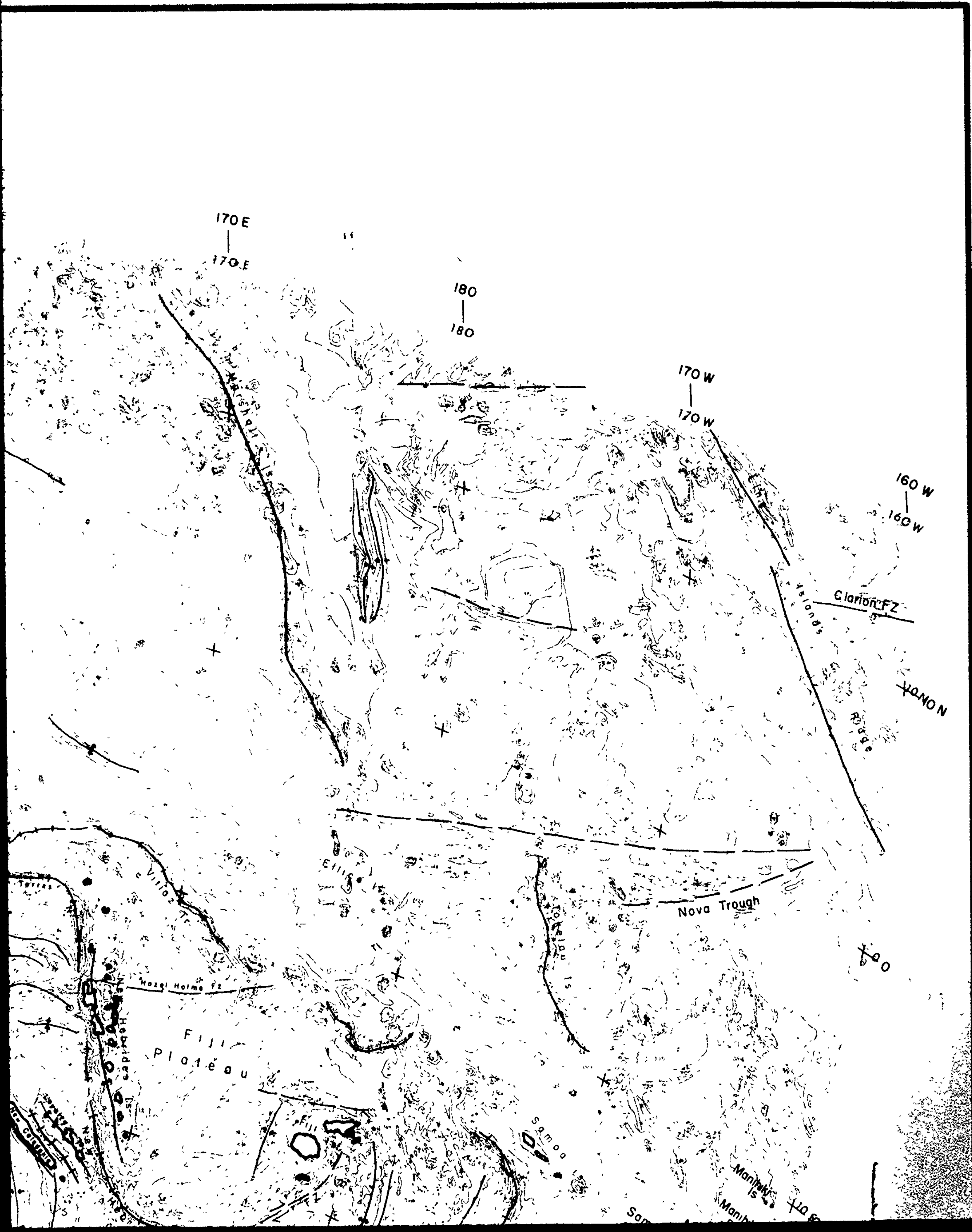


120E
110E
100E
90 E
90E
10 N
0
10 S
20 S
20S
Indochina
South China Sea
Gulf of Siam
Andaman Sea
Sunda Shelf
Celebes Basin
Java Sea
Java
Edge of Shelf
Java Trench
Shelf
Makassar Basin
Philippine

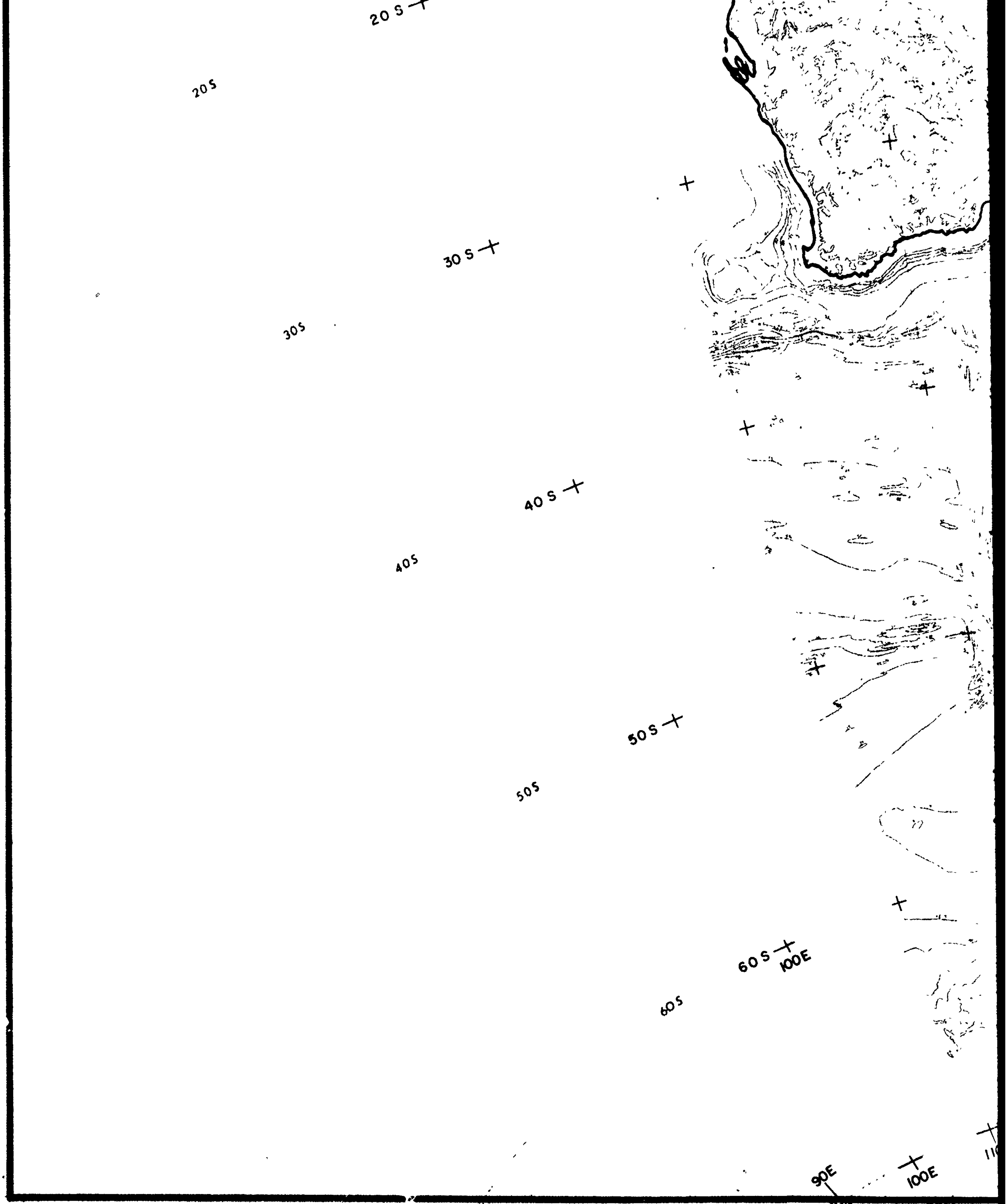
2


130E
130 E
140E
140 E
150E
150 E
160E
160 E
West Philippine Basin
Mariana Basin
Caroline Islands
West Caroline Basin
Eauripik – New Guinea Rise
East Caroline Basin
Mussau Tr.
New Guinea Trough
W. Melanesian Trough
? (Solomon Rise)
Ontong Java Plateau
New Guinea
Bismark Sea
New Britain
Solomon Sea
Solomon Is.
Papua
Arafura Sea
Timor Trough
Sea
Woodlark Basin
Coral Sea
New Hebrides Is.
Australia

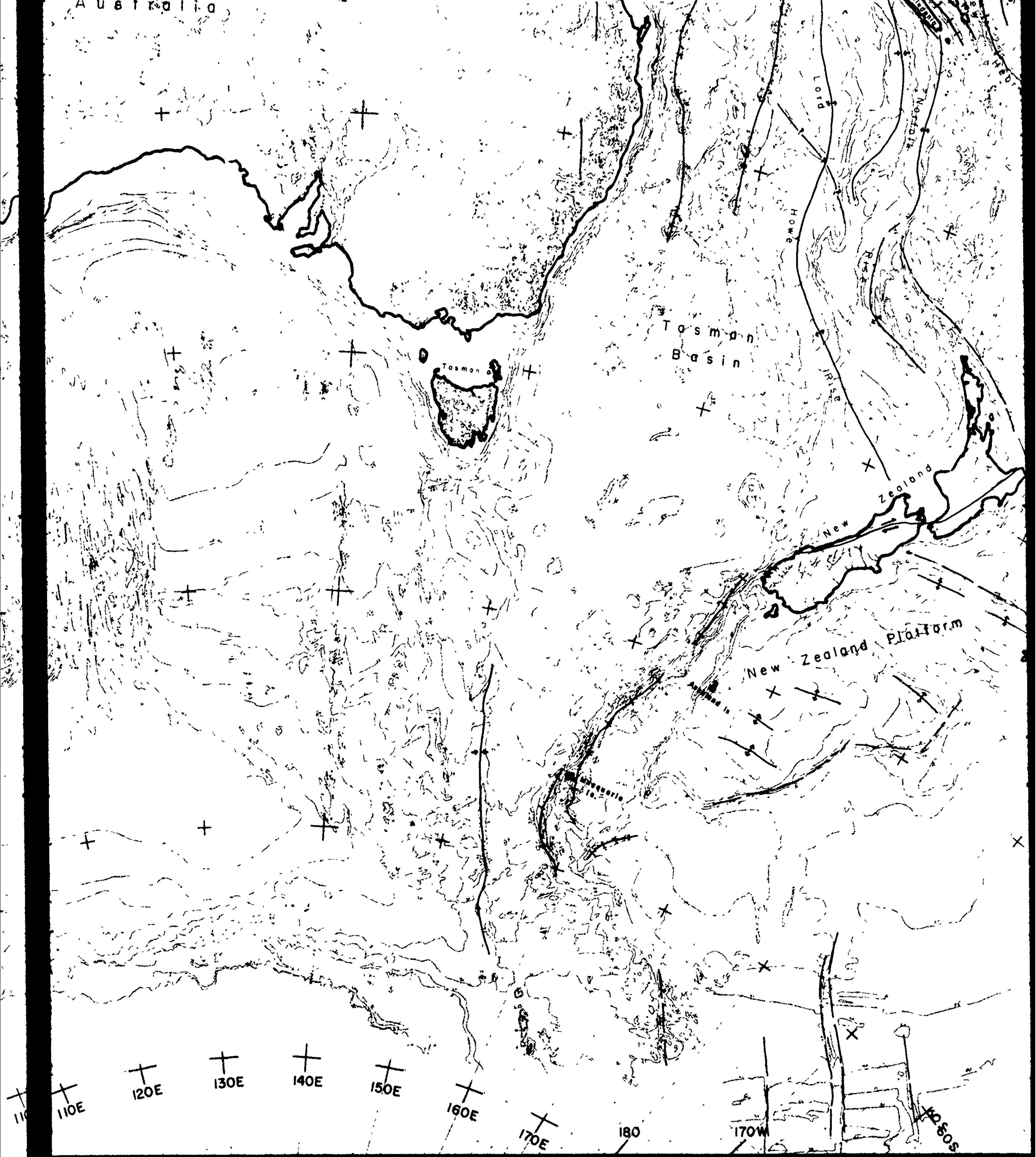
3



170 E
170 E
180
180
170 W
170 W
160 W
160 W
Clarion FZ
Islands
Ridge
10 N
Ellice Is
Nova Trough
Vitiaz Tr
Hazel Holme Fz
Fiji
Plateau
Fiji
Samoa
Manihiki Is

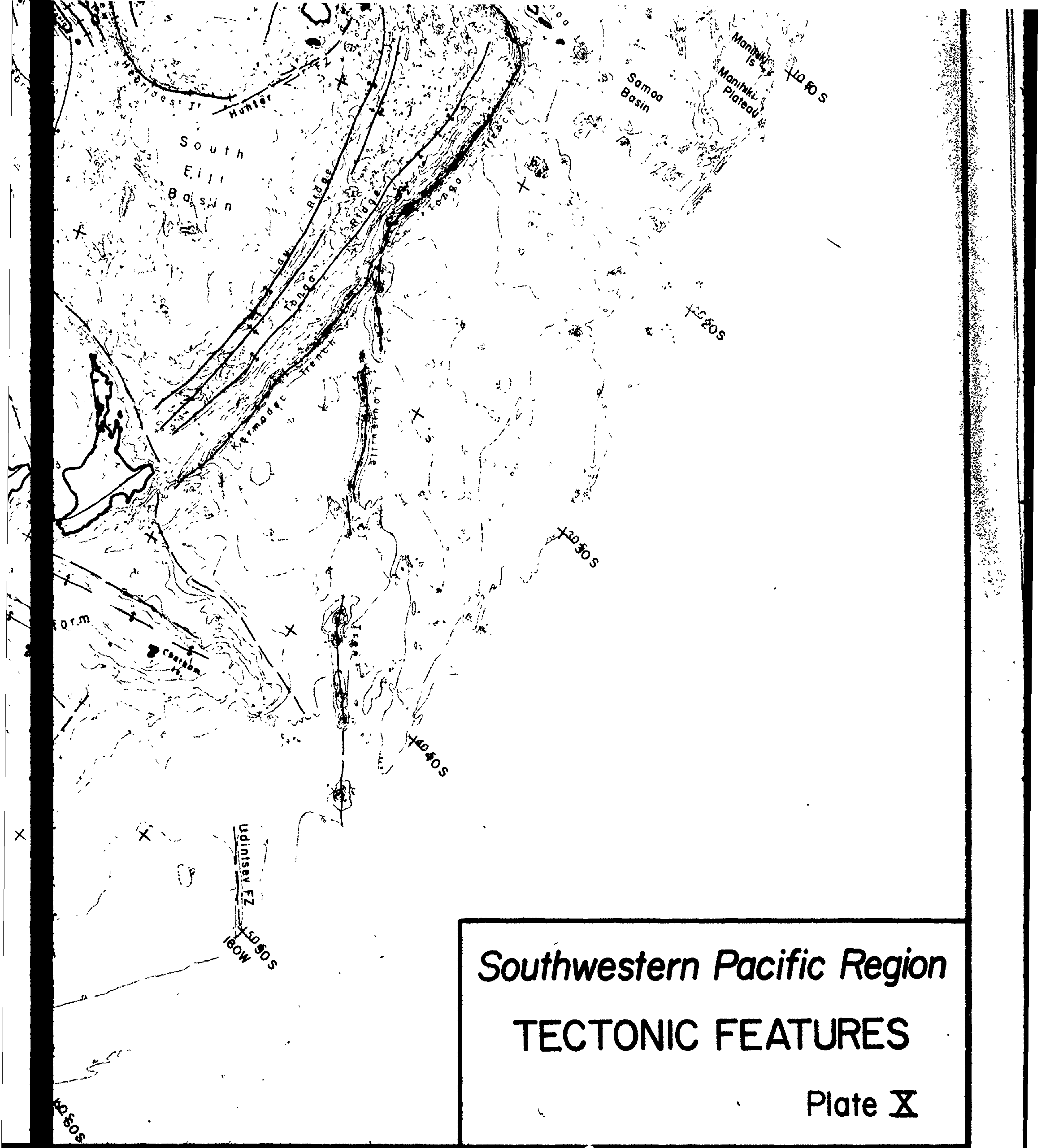


4



Australia
Tasman Basin
Lord Howe Rise
Norfolk
New Zealand
New Zealand Platform
Macquarie Is.
110E
120E
130E
140E
150E
160E
170E
180
170W
60S

5



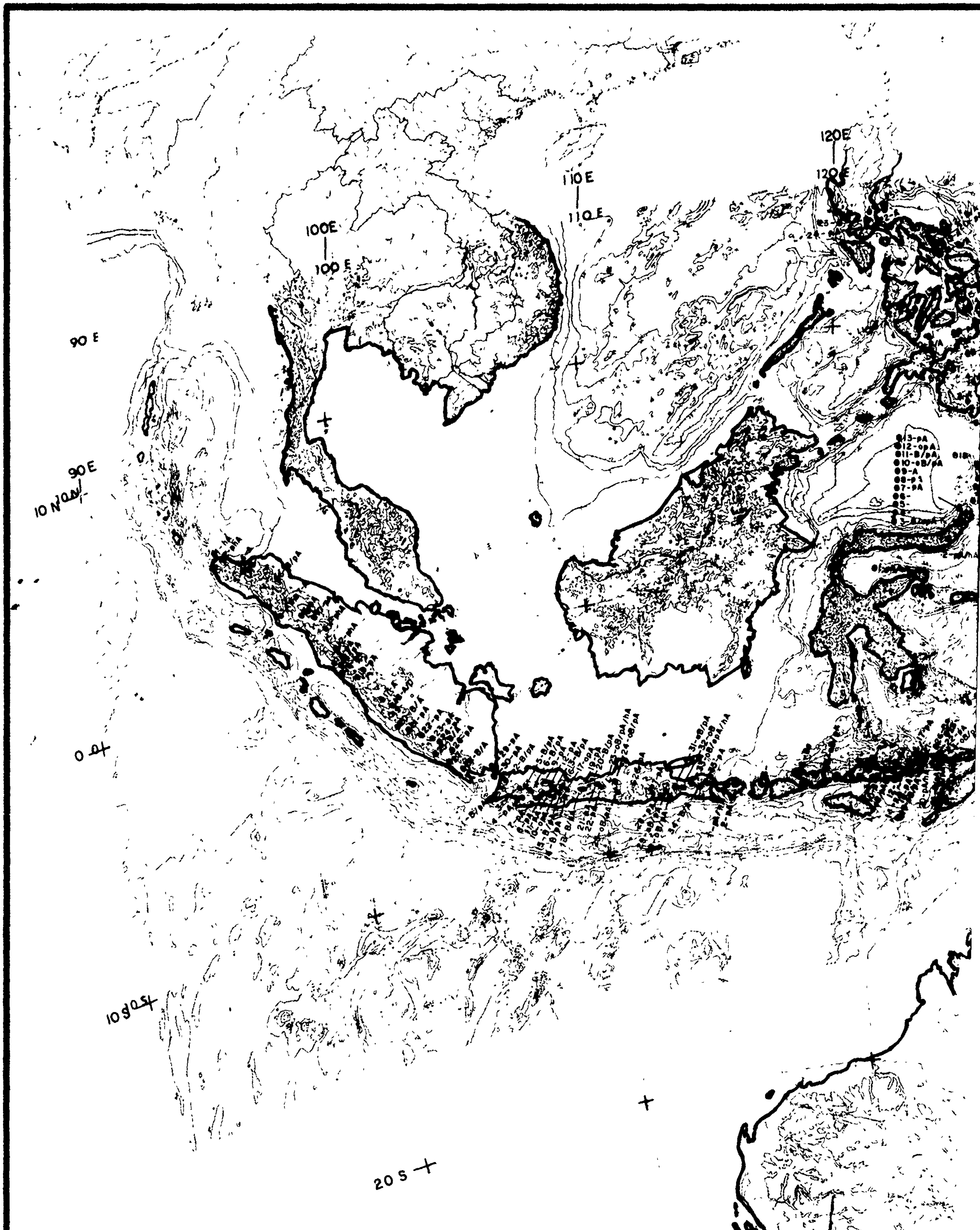
Southwestern Pacific Region

TECTONIC FEATURES

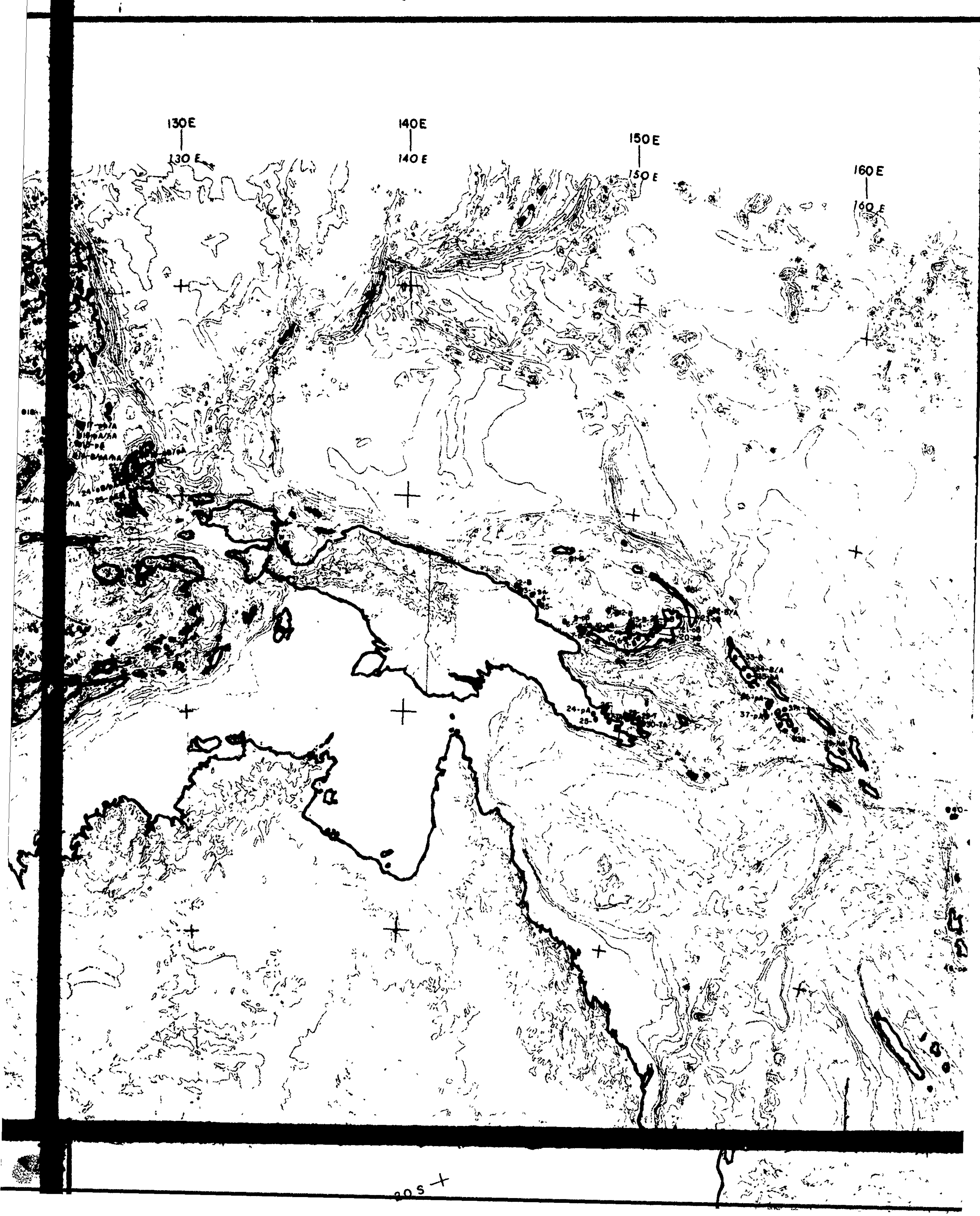
Plate X

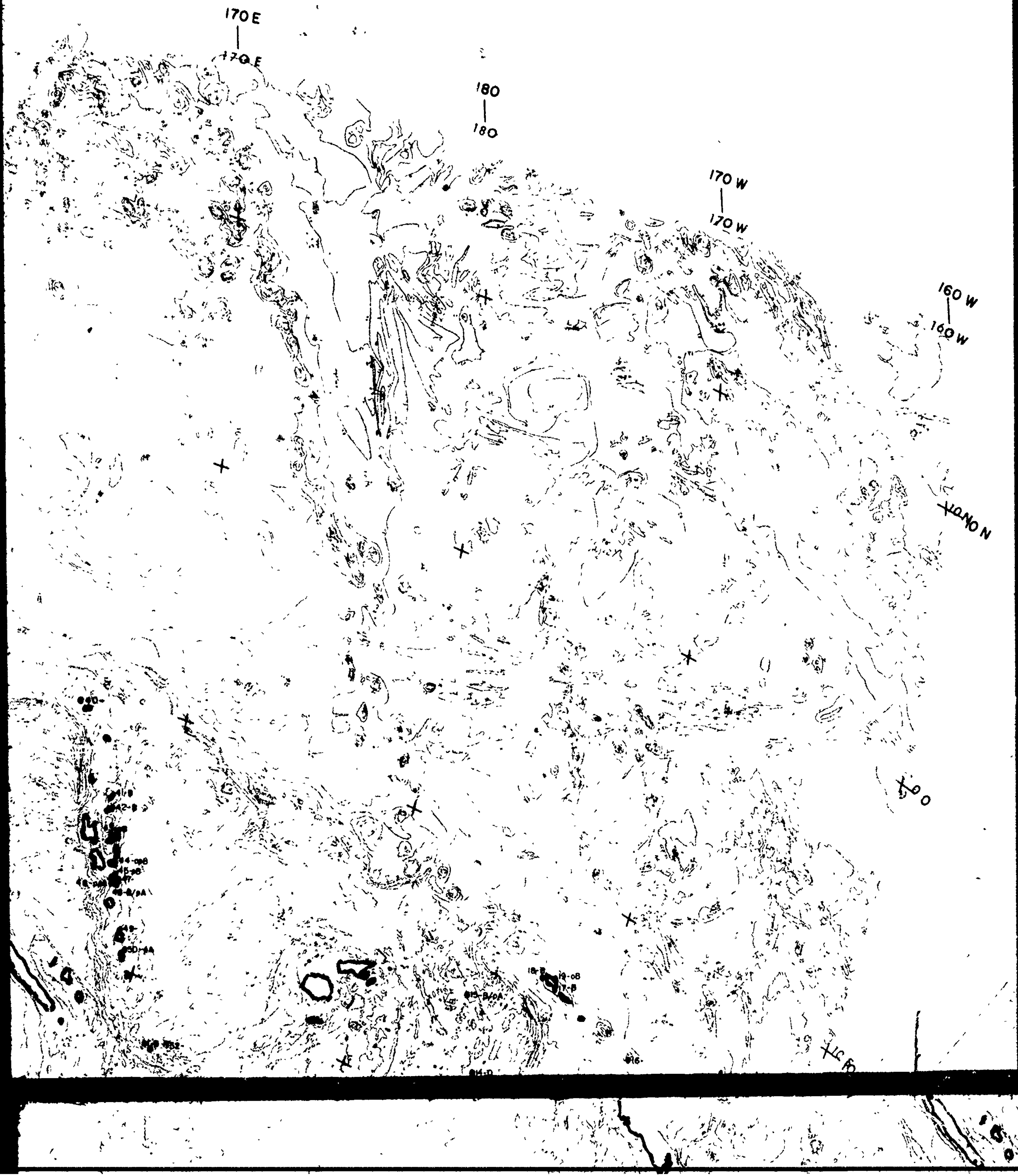
6

7

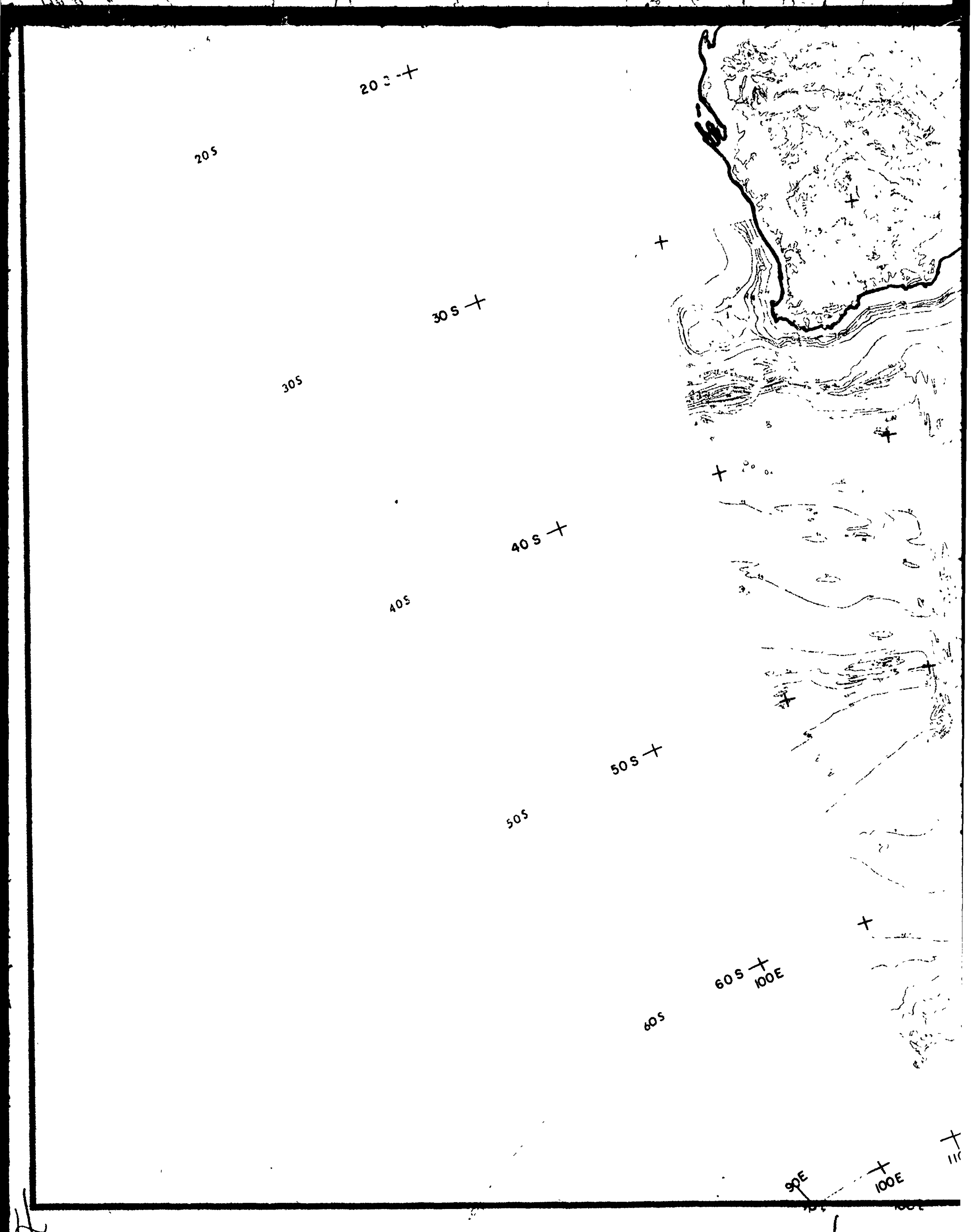


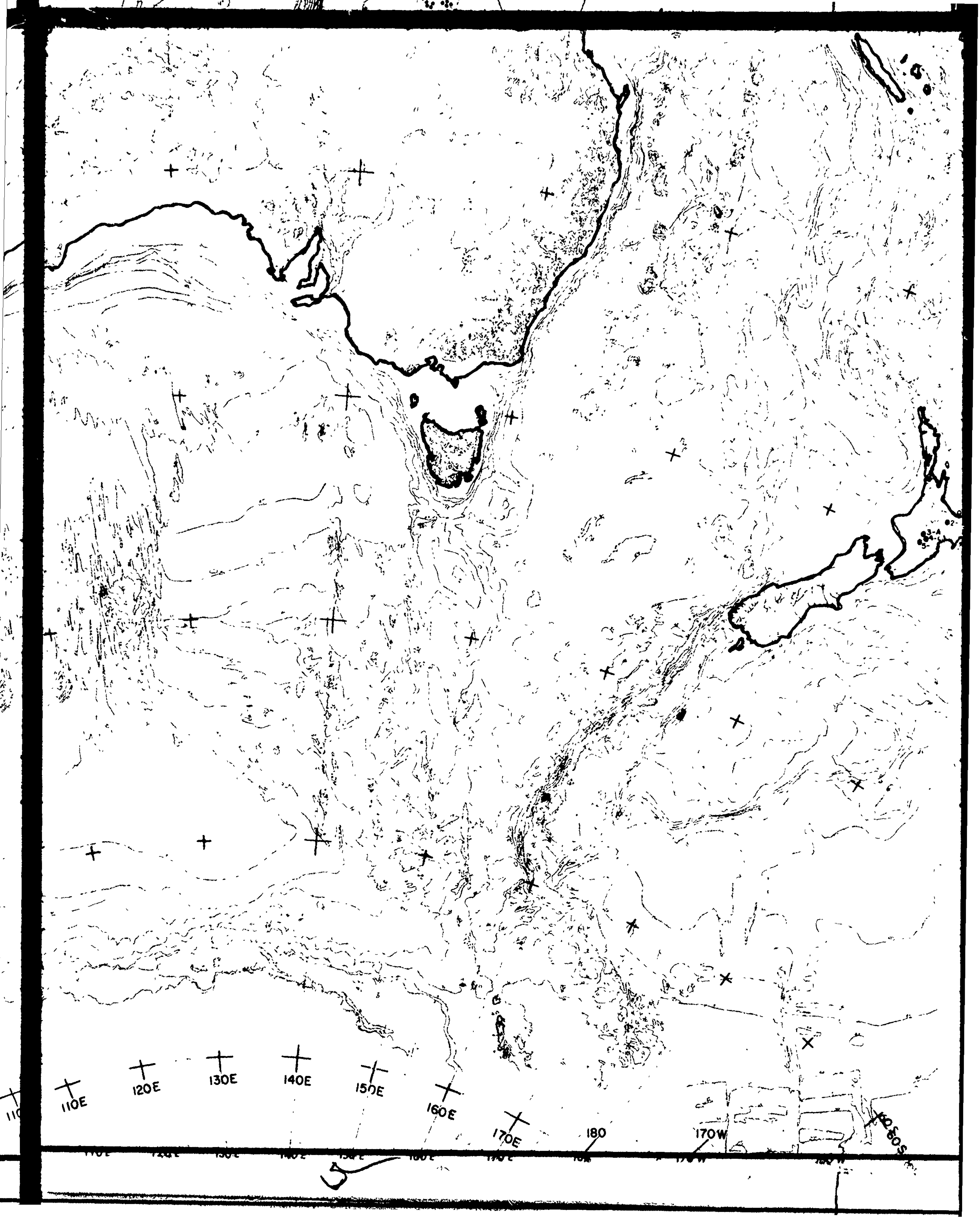
3

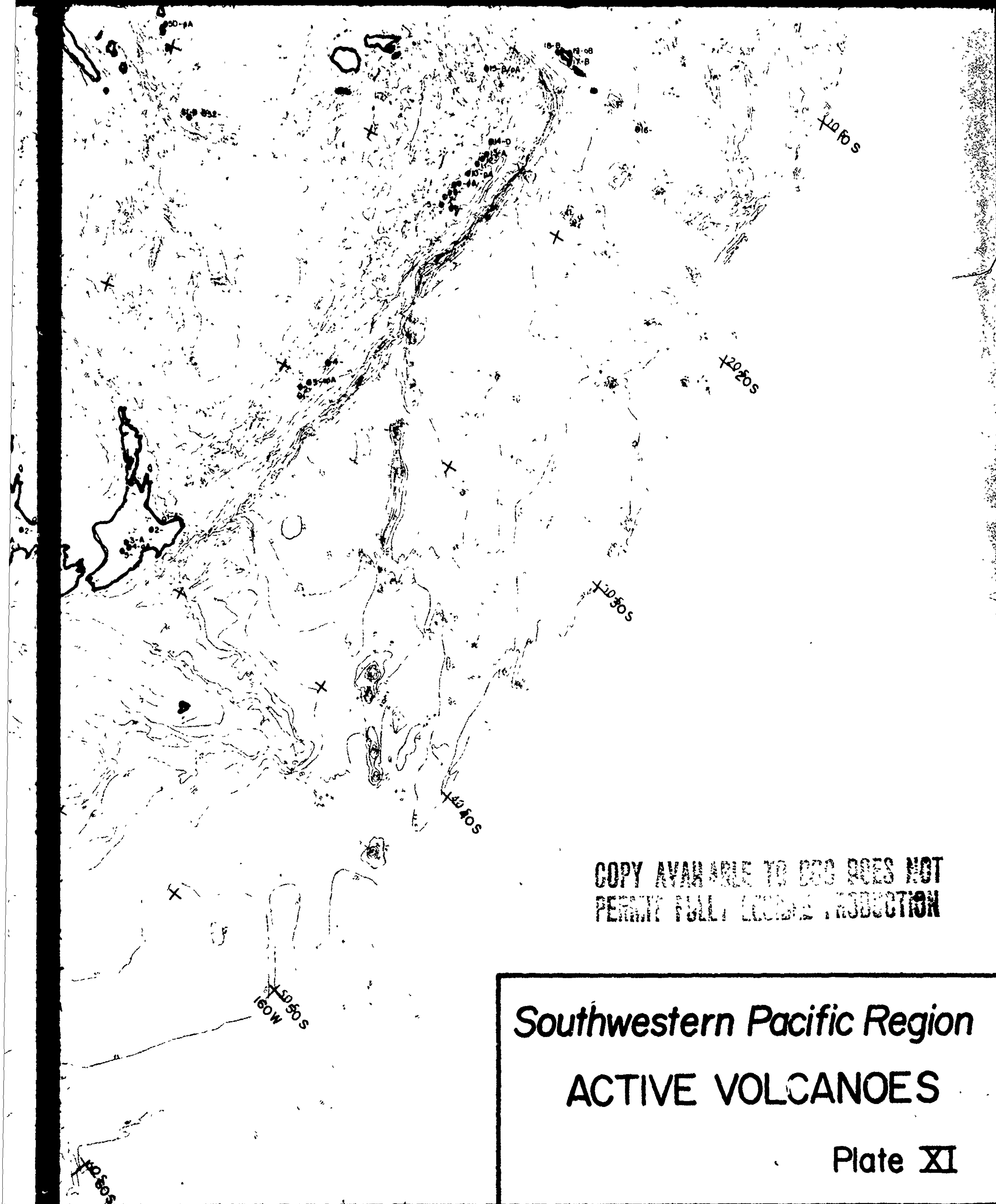

130E
130 E
140E
140 E
150E
150 E
160E
160 E
20S



170 E
170 E
180
180
170 W
170 W
160 W
160 W
10 N
0


20 S
20S
30 S
30S
40 S
40S
50 S
50S
60 S
100E
60S
90E
100E

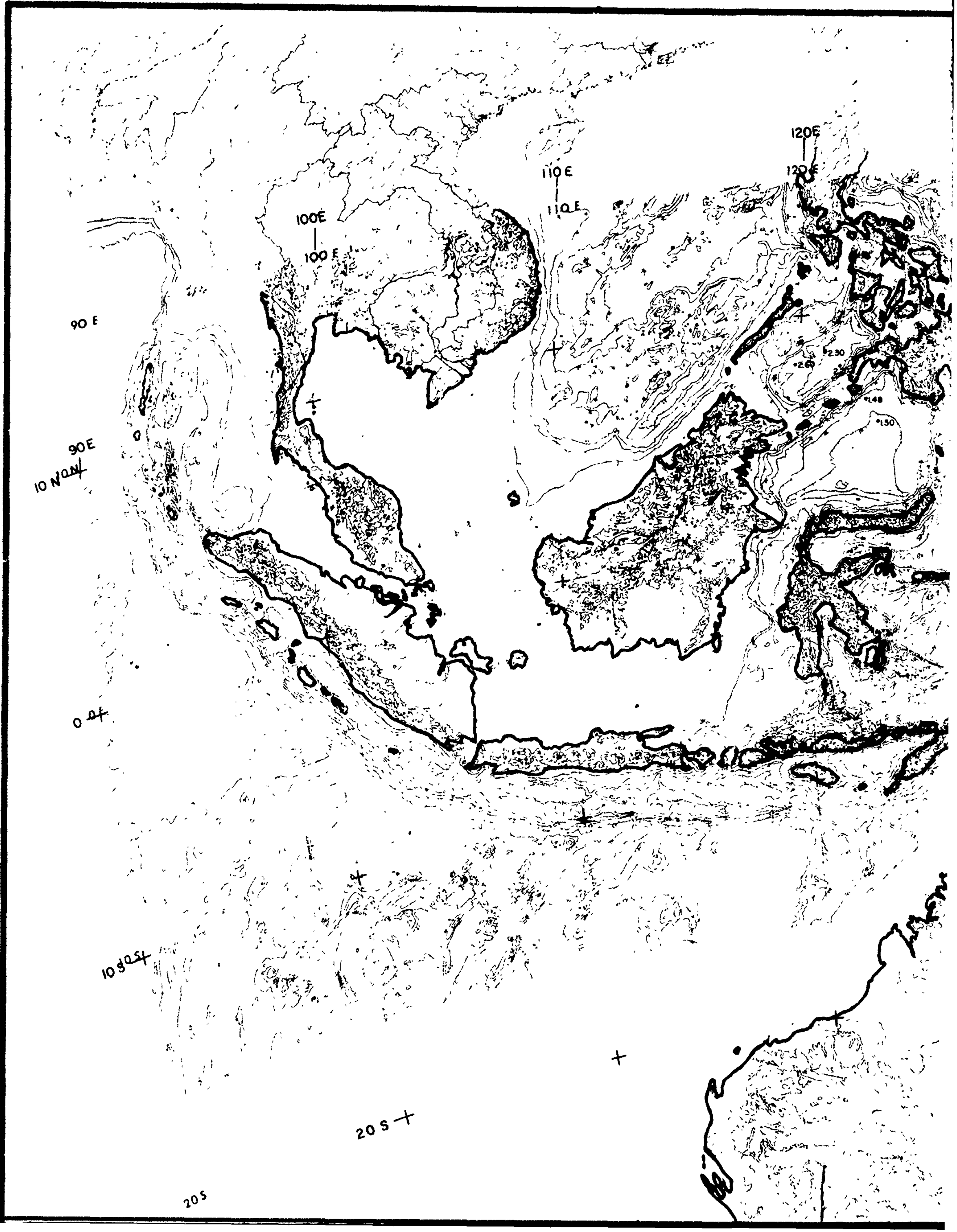

110E
120E
130E
140E
150E
160E
170E
180
170W
60S



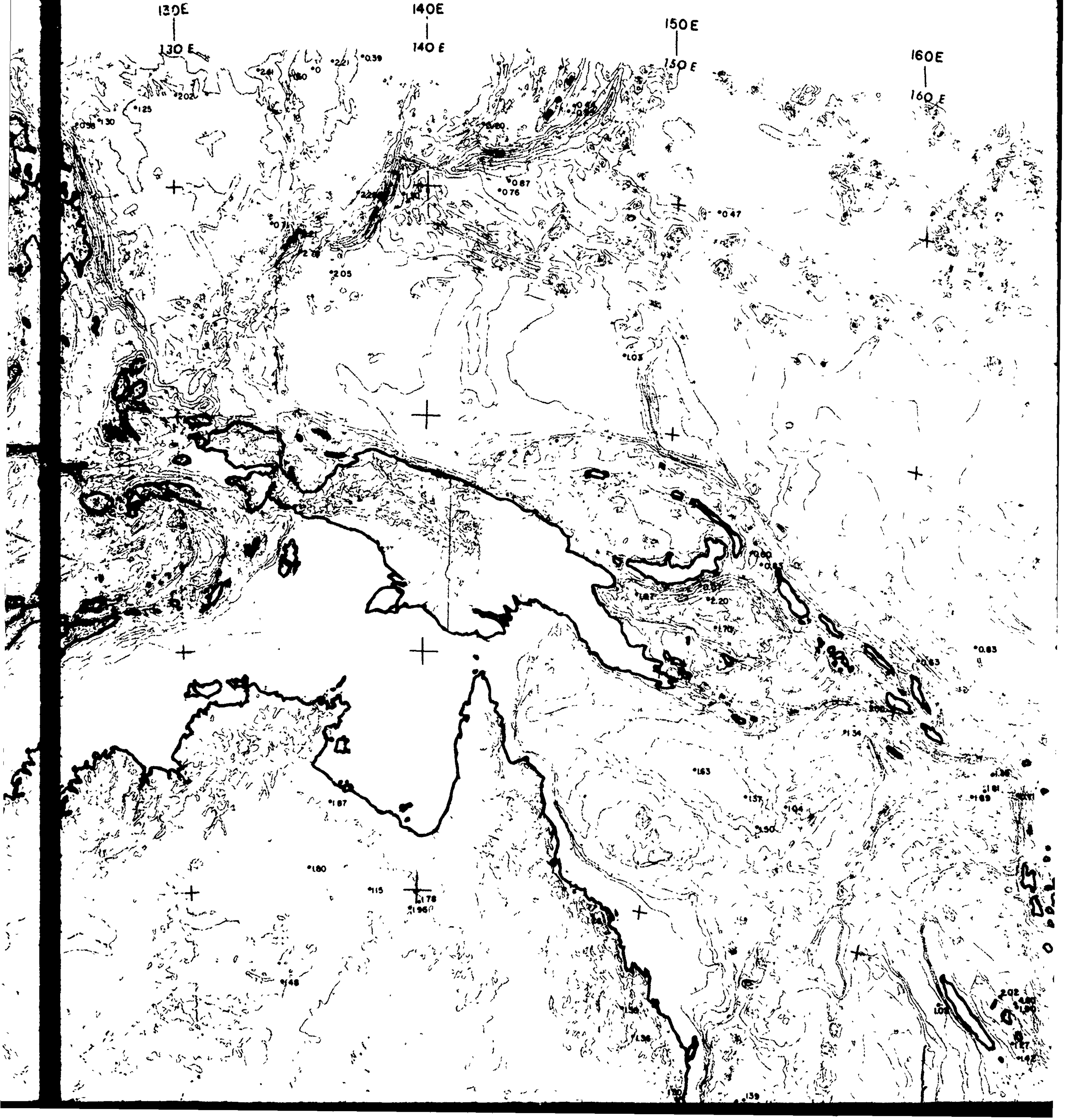
Southwestern Pacific Region

ACTIVE VOLCANOES

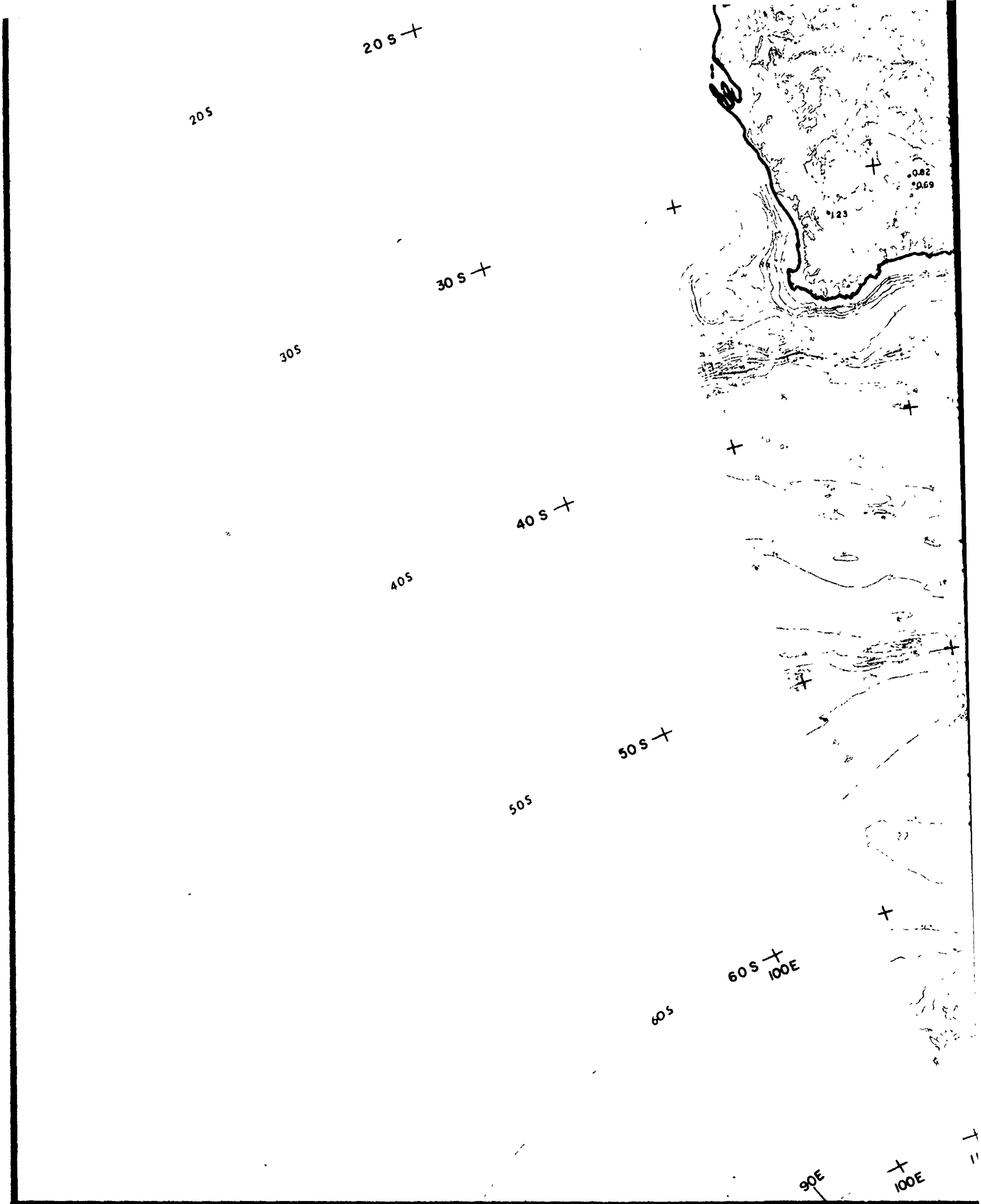
Plate XI


120E
120E
110E
110E
100E
100E
90E
90E
10N
10N
0
10S
10S
20S
20S
230
260
148
150

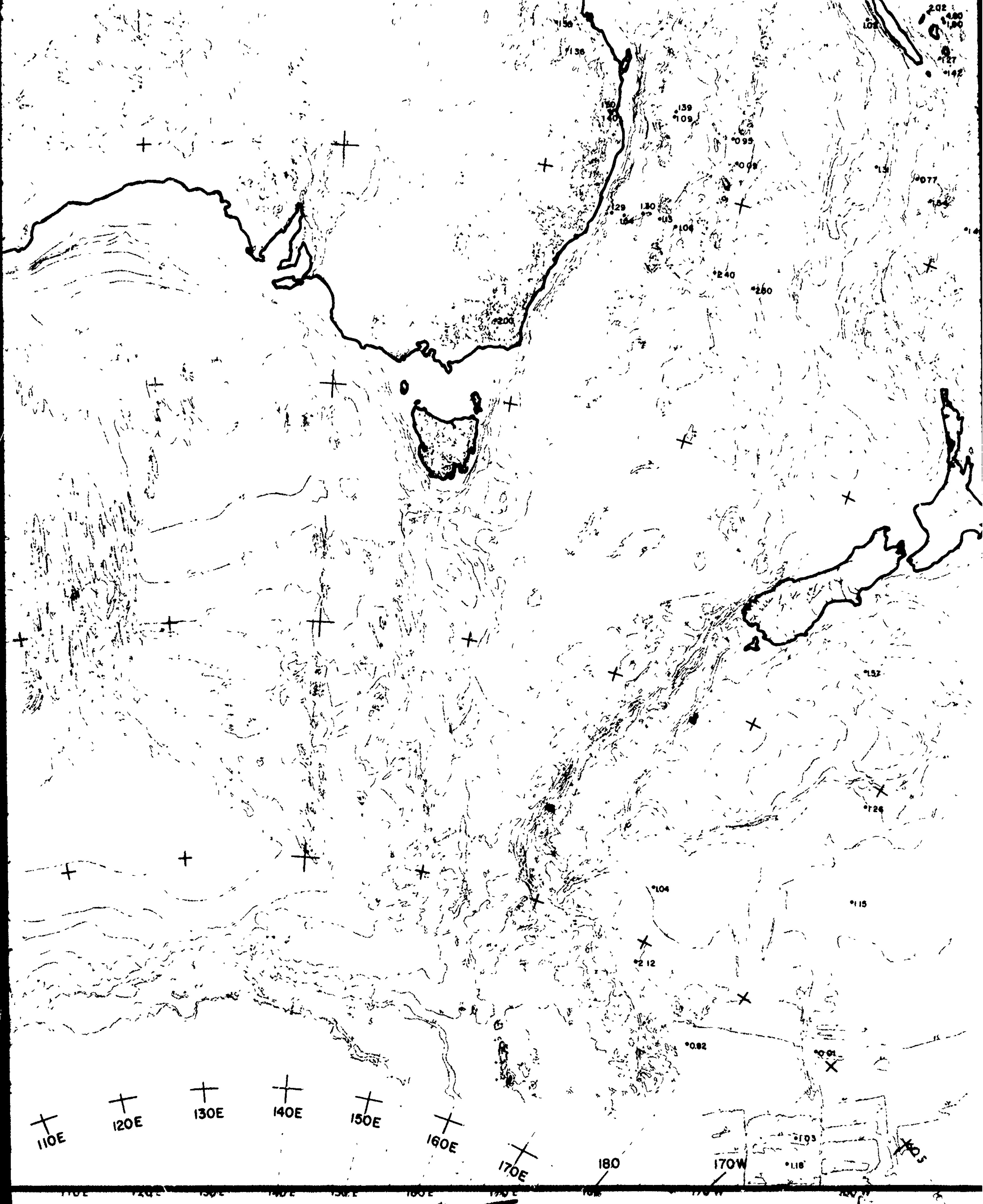
2



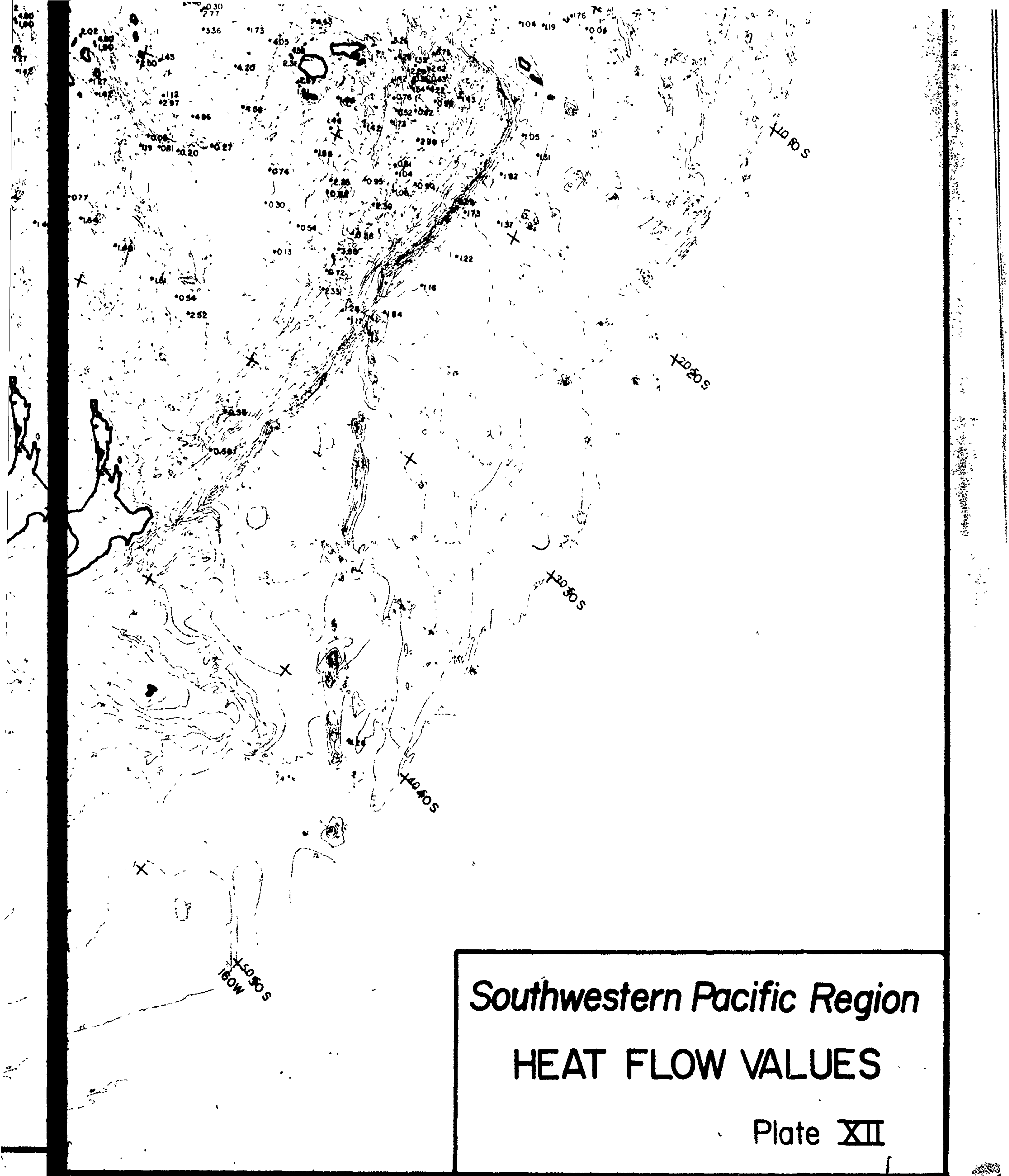
3


20 S
20S
0.82
0.69
123
30 S
30S
40 S
40S
50 S
50S
60 S
100E
60S
90E
100E

4



5

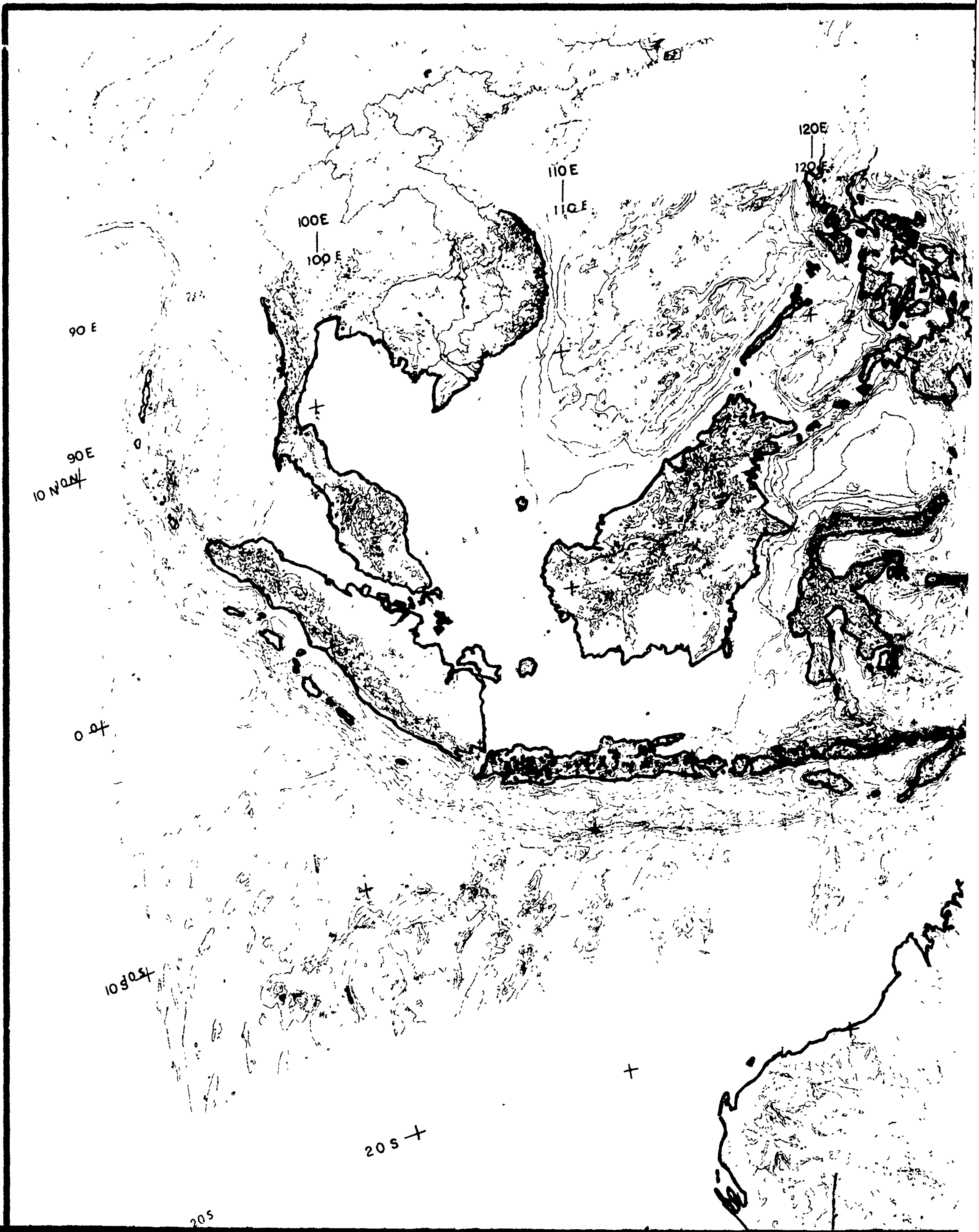


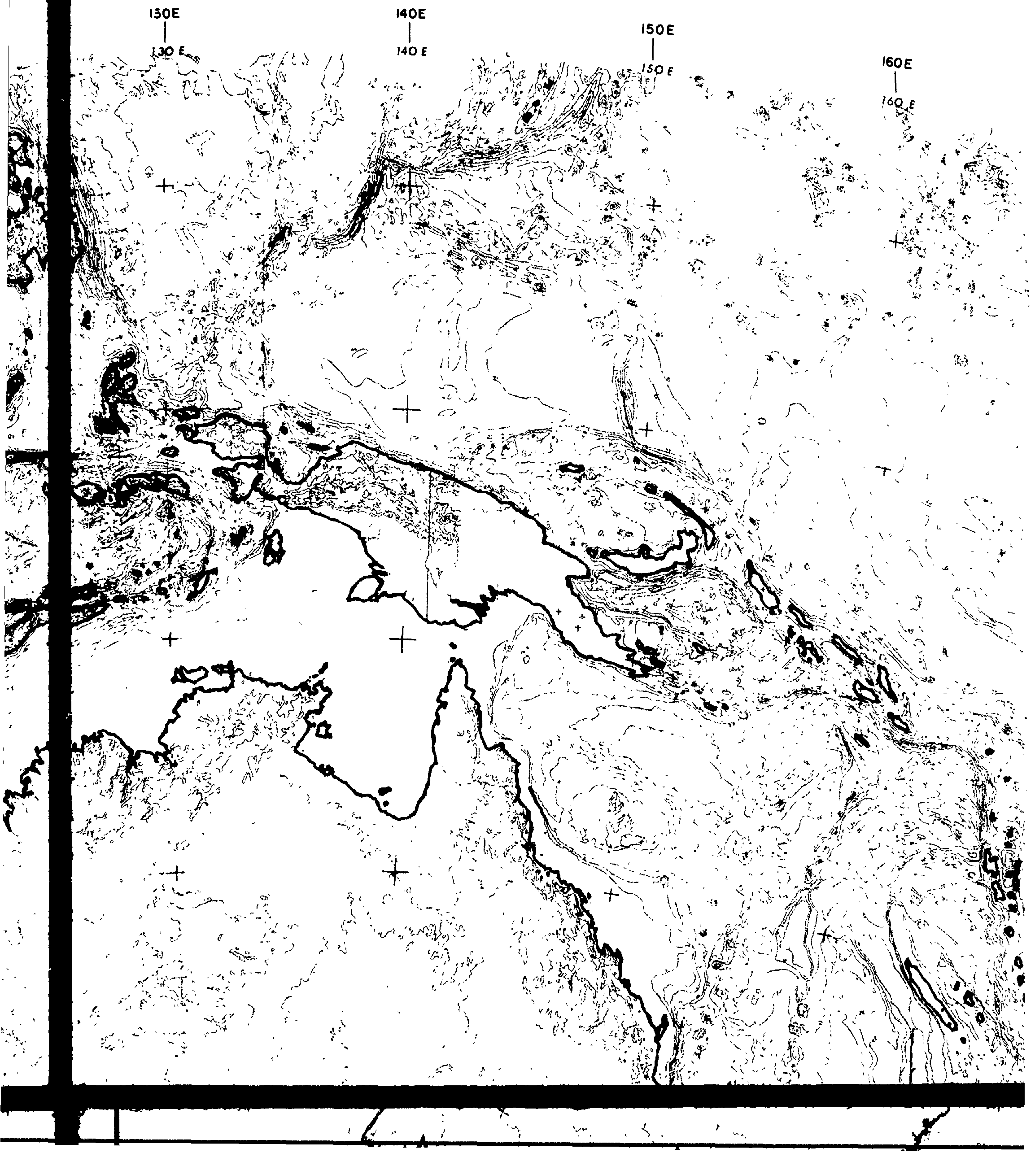
Southwestern Pacific Region

HEAT FLOW VALUES

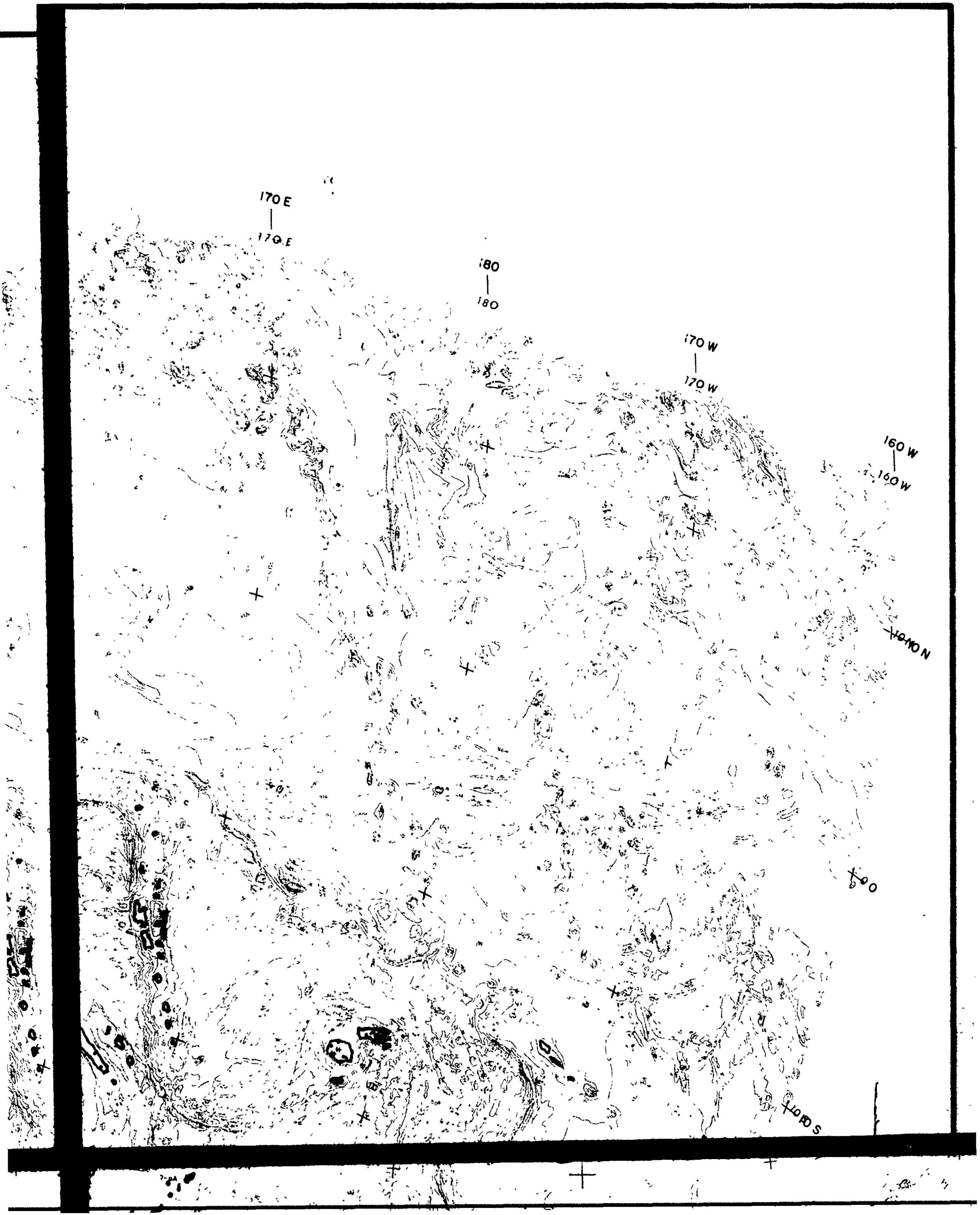
Plate XII

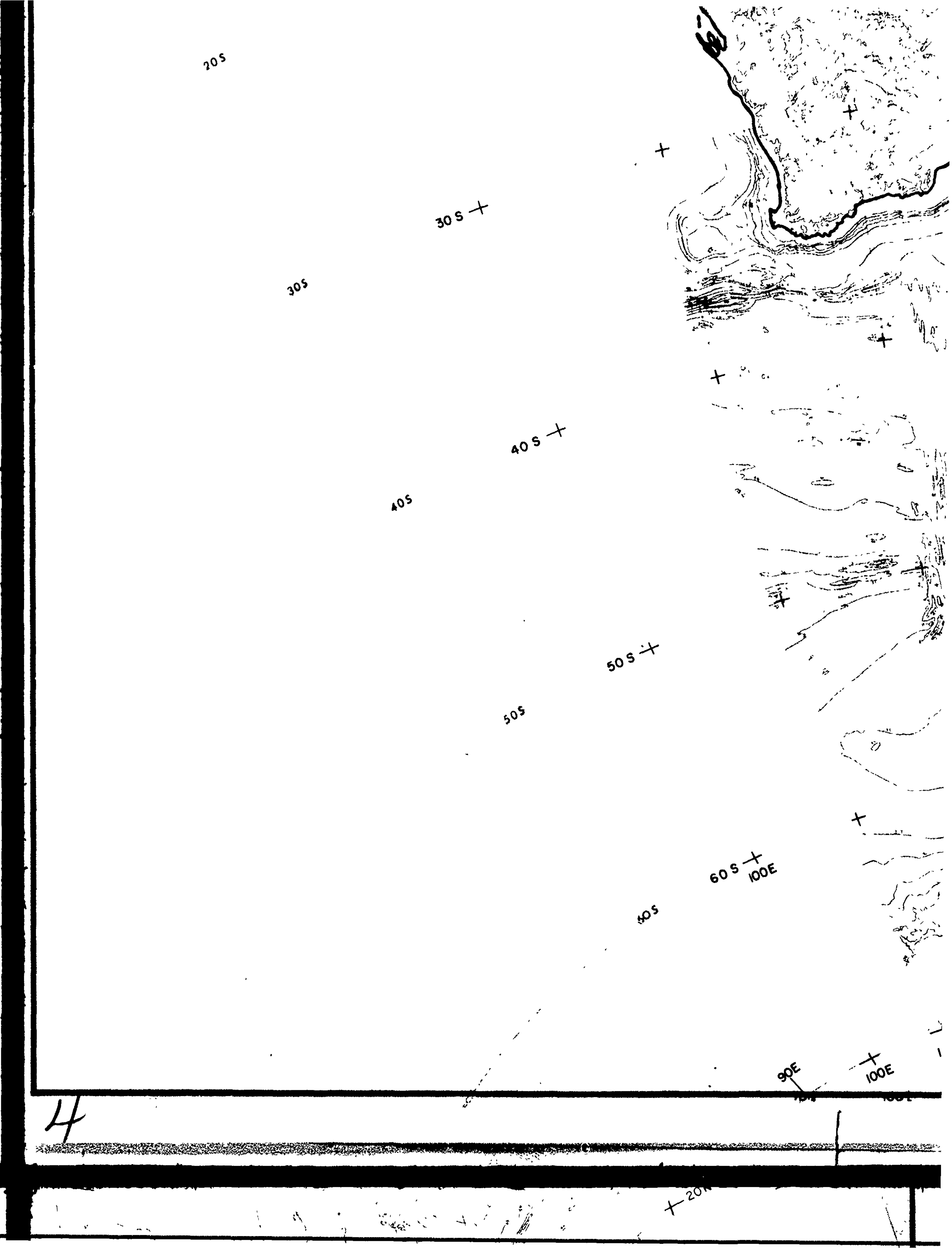
1



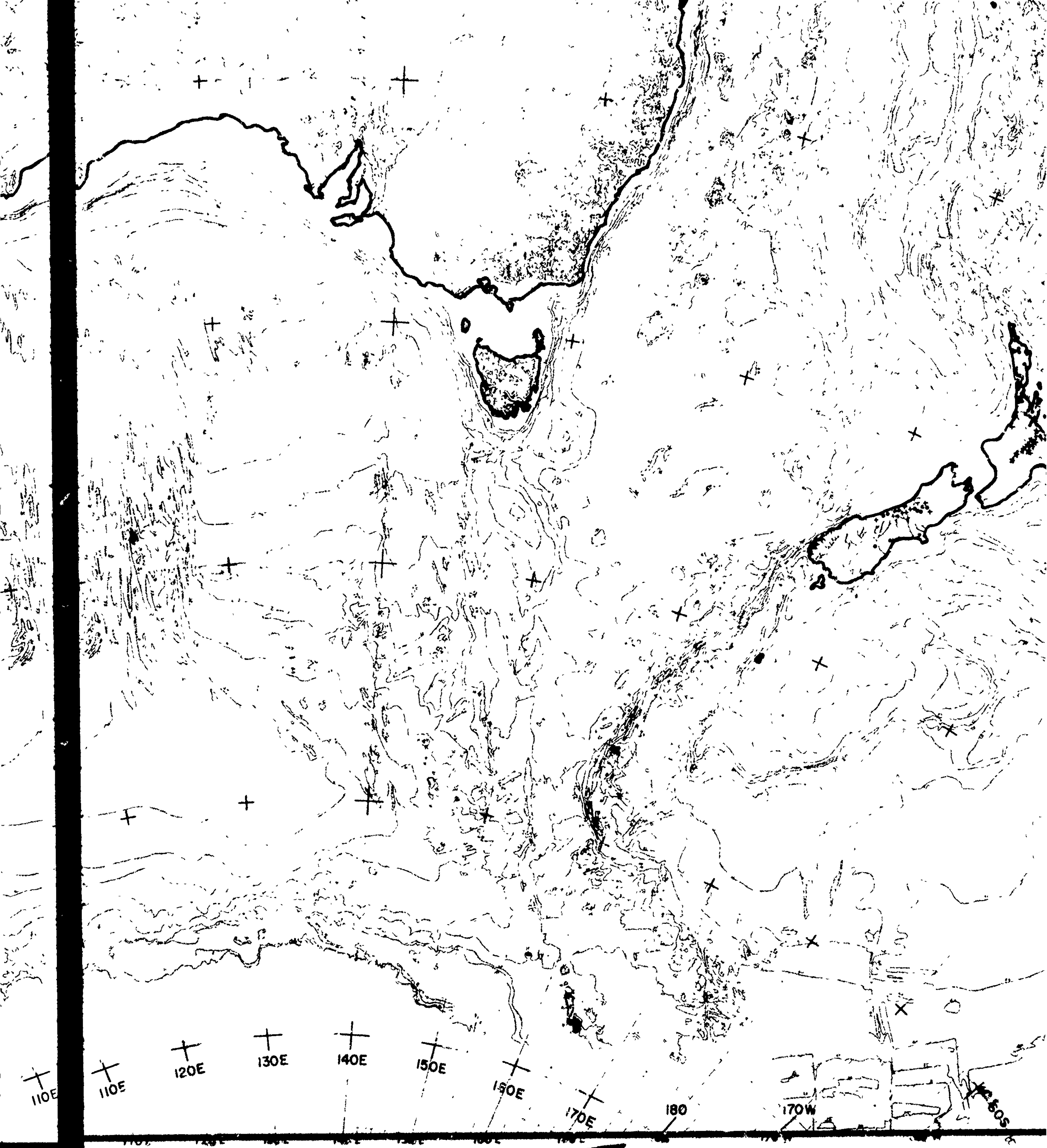


130E
130 E
140E
140 E
150E
150 E
160E
160 E


170 E
170 E
180
180
170 W
170 W
160 W
160 W
10 N
0
10 S

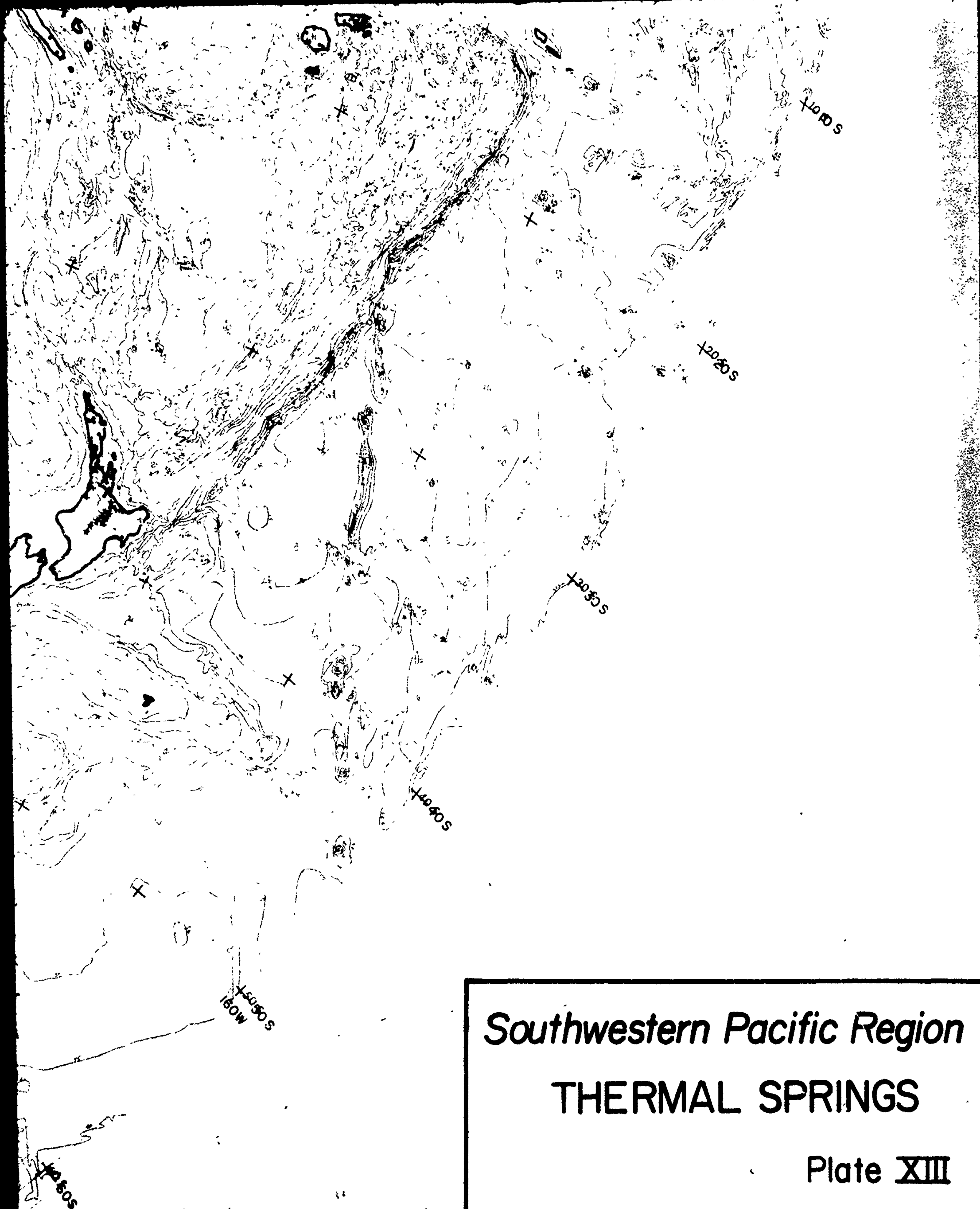


4



5

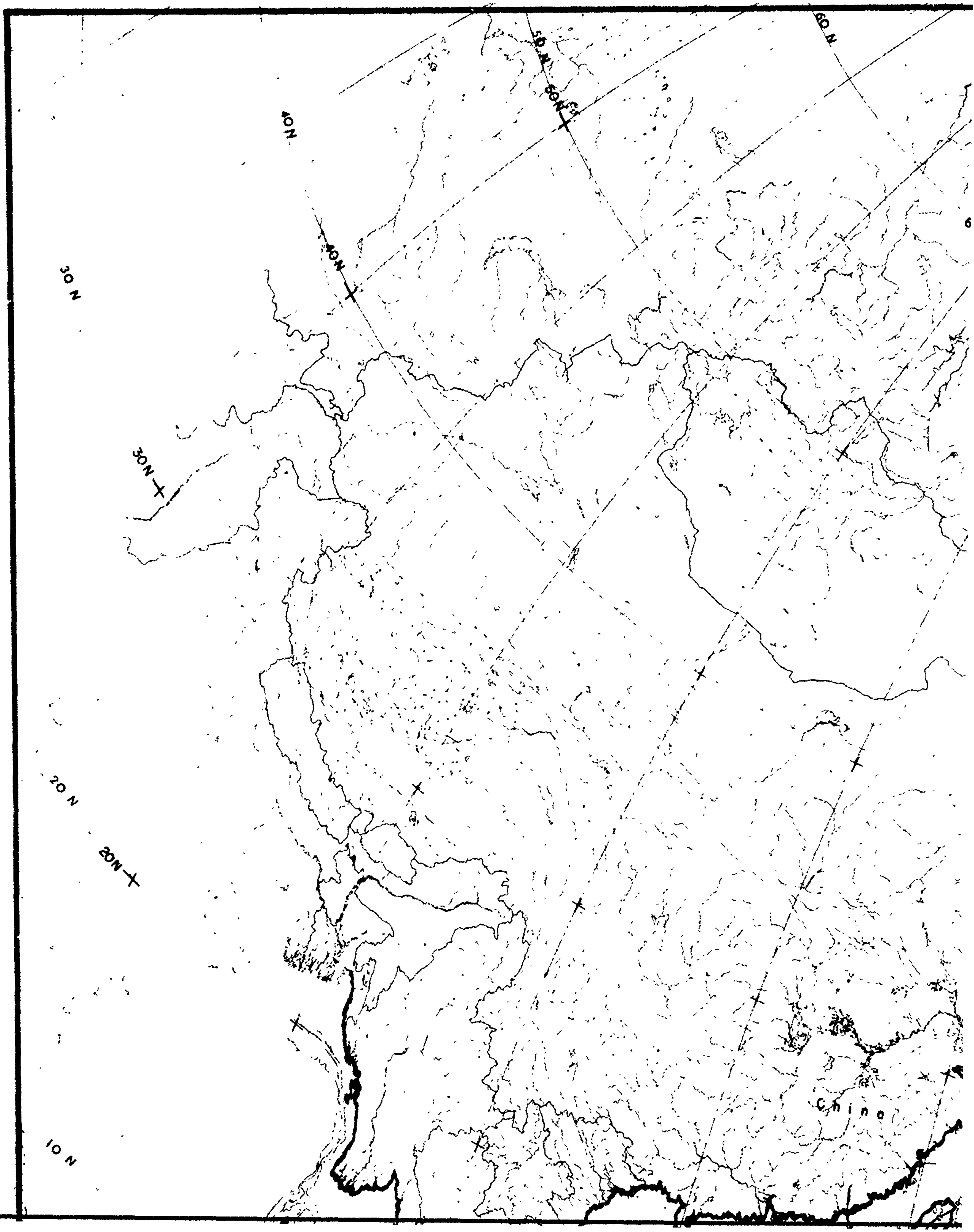
1



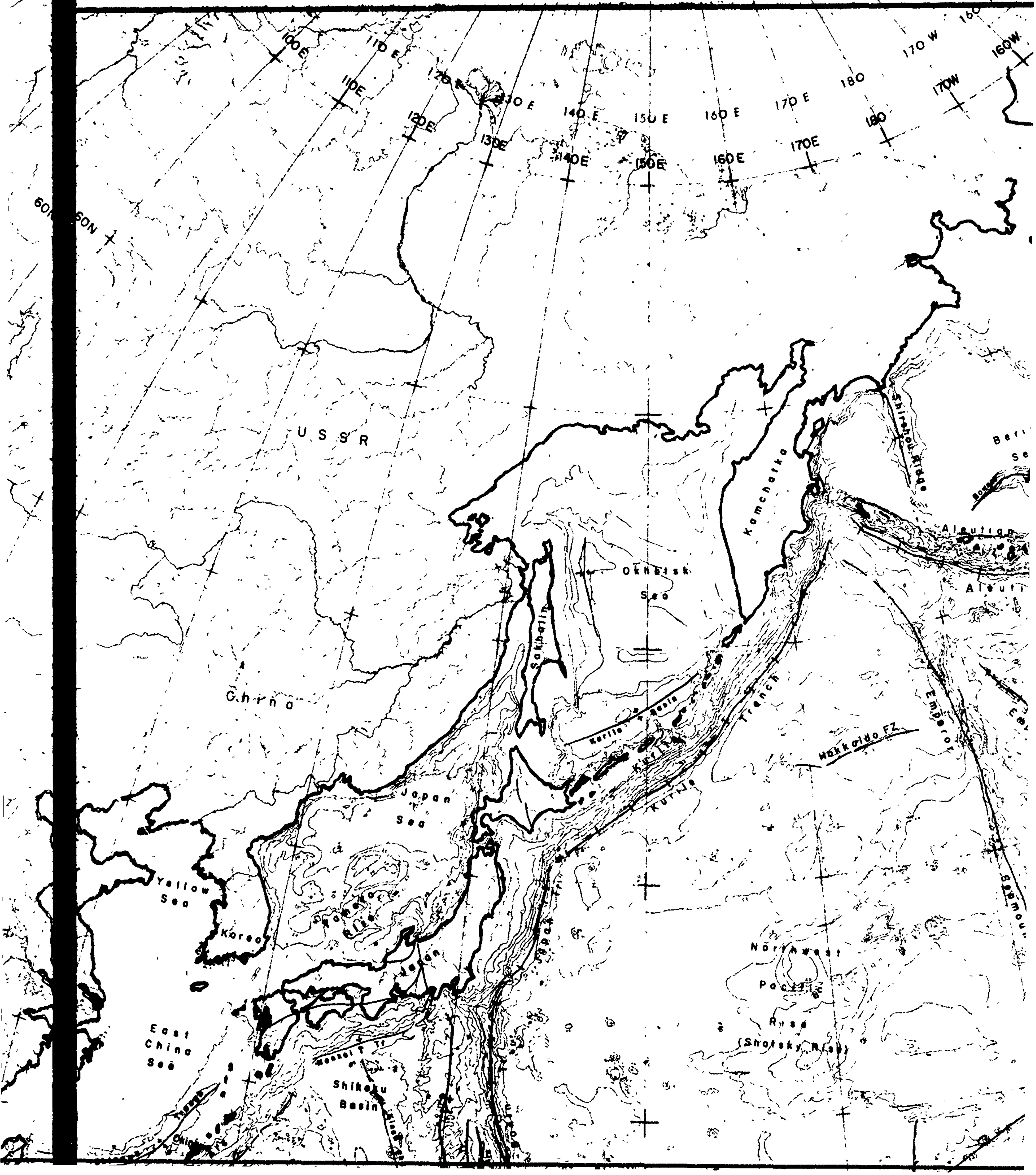
Southwestern Pacific Region

THERMAL SPRINGS

Plate XIII


60 N
50 N
50N
40N
40N
30 N
30N
20 N
20N
10 N
China

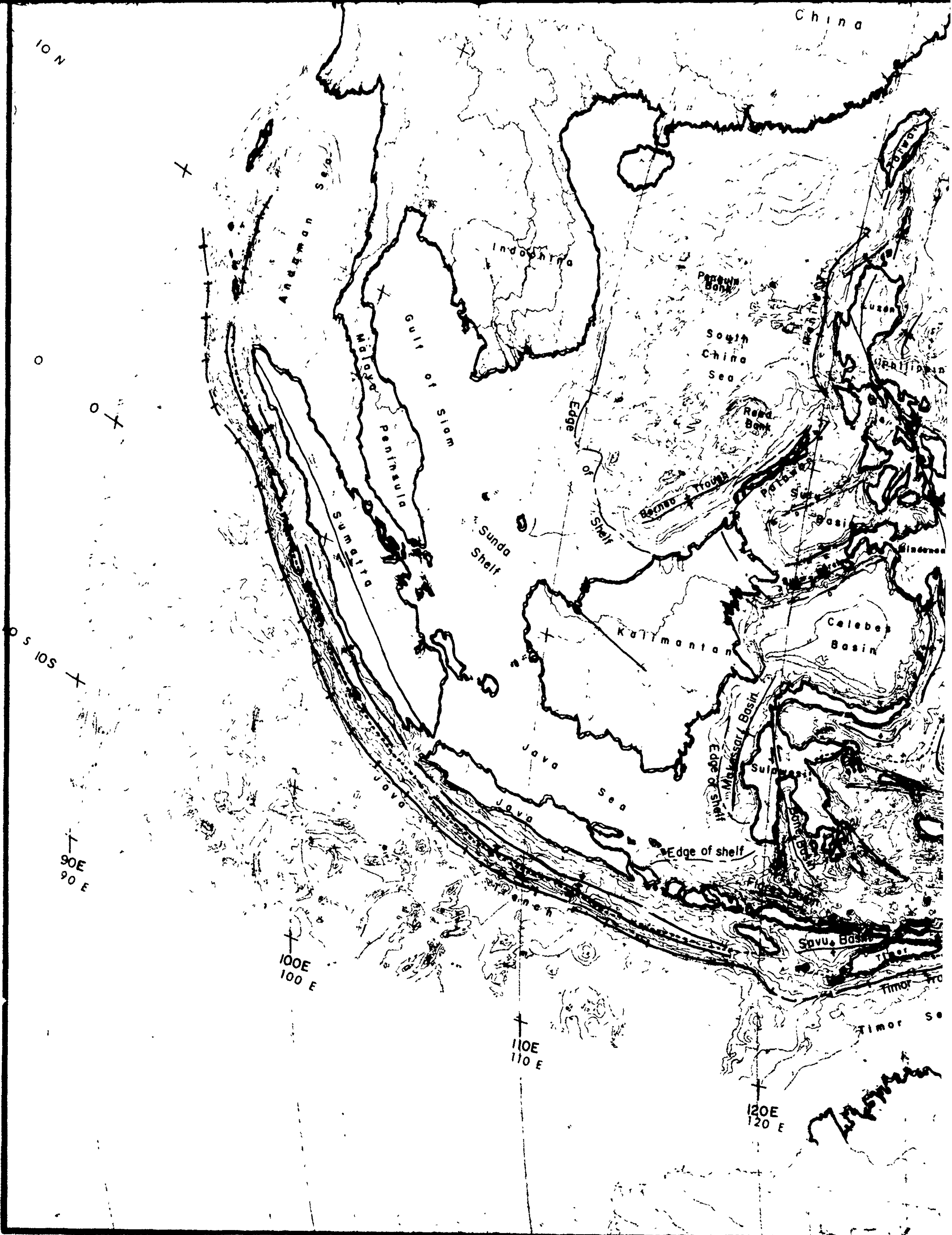
2



100E
110E
120E
130E
140E
150E
160E
170E
180
170W
160W
60N
USSR
China
Okhotsk Sea
Kamchatka
Sakhalin
Shirshov Ridge
Aleutian
Kurile Trench
Hokkaido FZ
Emperor
Japan Sea
Yellow Sea
Korea
Japan
Japan Trench
East China Sea
Nankai Tr
Shikoku Basin
Northwest Pacific Rise
(Shatsky Rise)

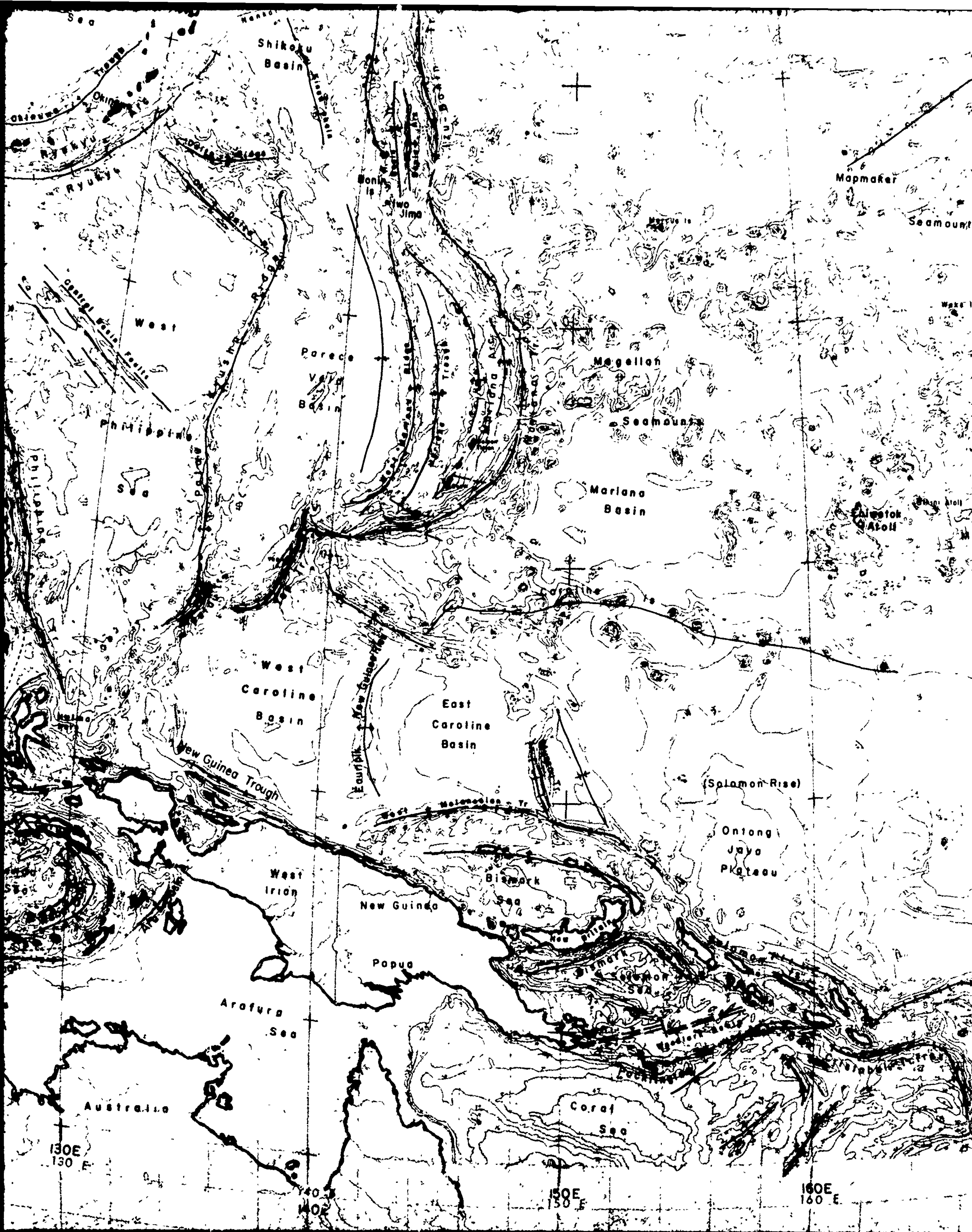
3

170W
160W
60N
Bering Shelf
Bering Sea
50N
Bowers
Aleutian
Islands
Trench
Aleutian Abyssal Plain
Amlia FZ
Surveyor FZ
40N
Emperor
Emperor Trough
Wellish Plateau
Hess Rise
Mendocino FZ
Musicians Seamounts
30N
Seamounts
Murray FZ
Hawaiian
Archipelago
Niihau Is
Necker Ridge
20N
FZ

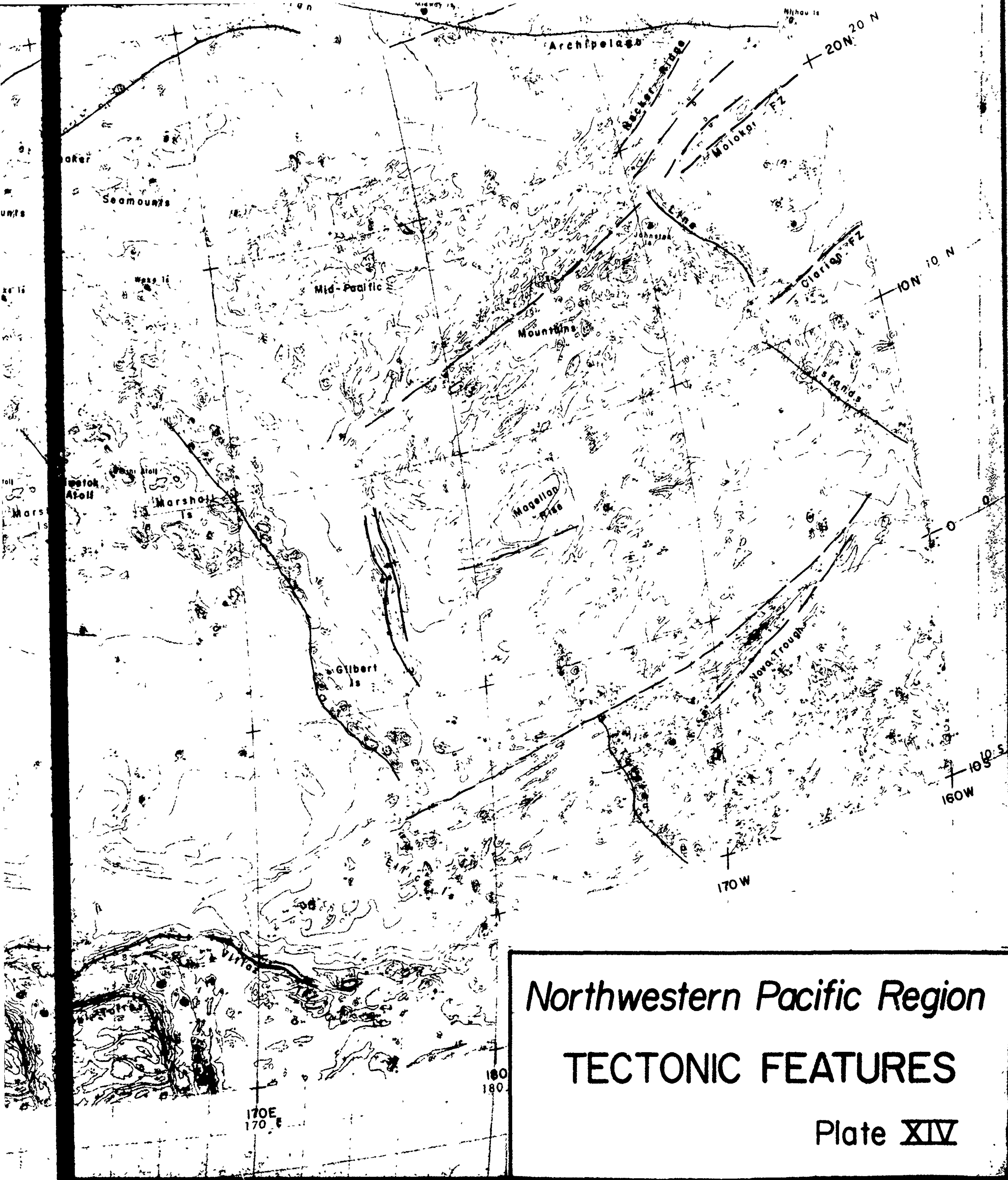


China
10 N
Andaman Sea
Indochina
Gulf of Siam
Malaya Peninsula
South China Sea
Reed Bank
Borneo Trough
Palawan
Sulu Basin
Luzon
Philippine
Mindanao
Edge of Shelf
Sunda Shelf
Sumatra
Kalimantan
Celebes Basin
Makassar Basin
Edge of Shelf
Sulawesi
Bone Basin
Flores Basin
Savu Basin
Timor Trough
Timor Sea
Java Sea
Java
Java Trench
Edge of shelf
10S
90E
90 E
100E
100 E
110E
110 E
120E
120 E

H



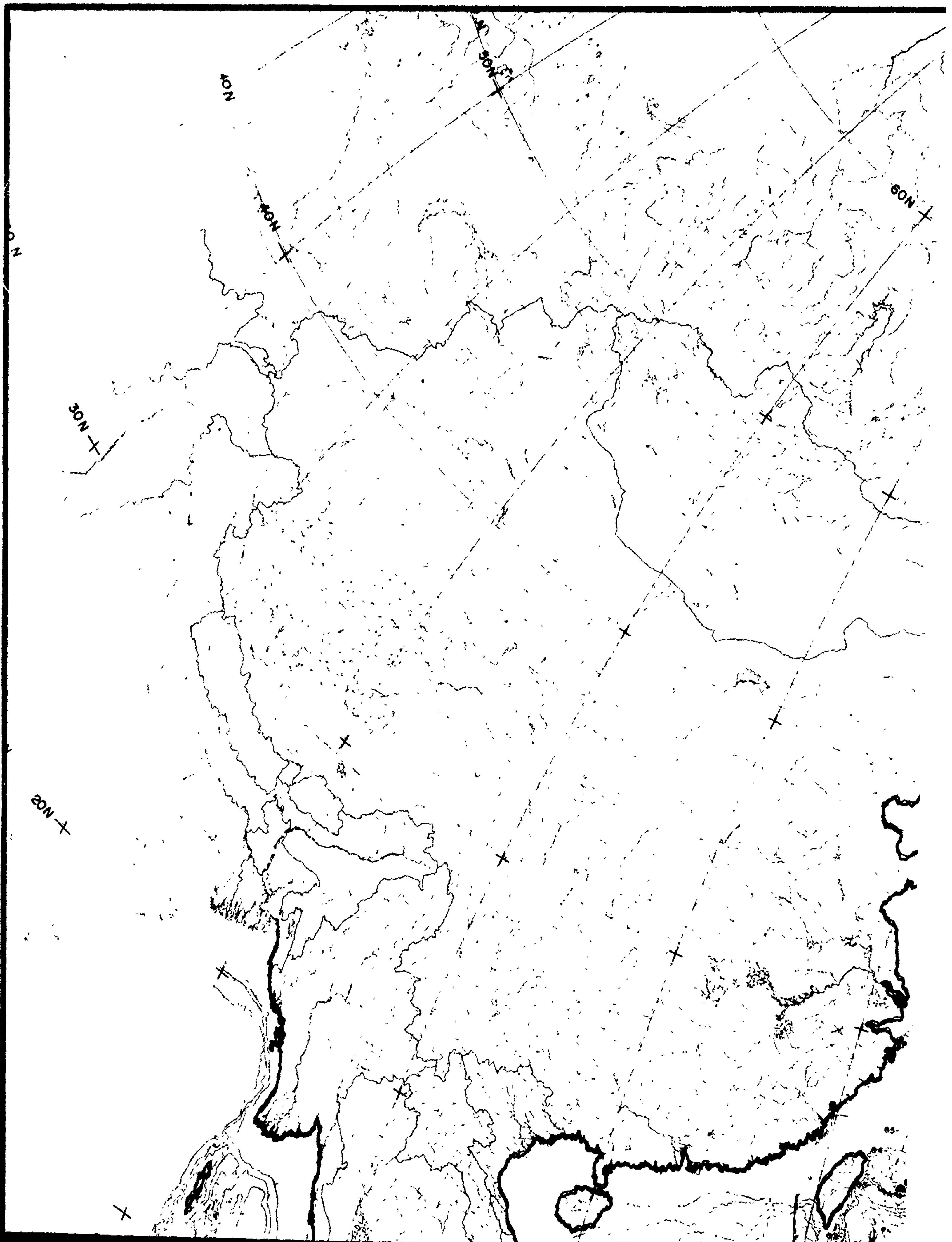
Shikoku Basin
Ryukyu
Bonin Is
Iwo Jima
Mapmaker Seamounts
West
Philippine
Sea
Parece Vela Basin
Magellan Seamounts
Mariana Basin
Eniwetok Atoll
Caroline Is
West Caroline Basin
East Caroline Basin
New Guinea Trough
(Solomon Rise)
Ontong Java Plateau
West Irian
New Guinea
Bismark Sea
Papua
Arafura Sea
Australia
Coral Sea
130E
140E
150E
160E



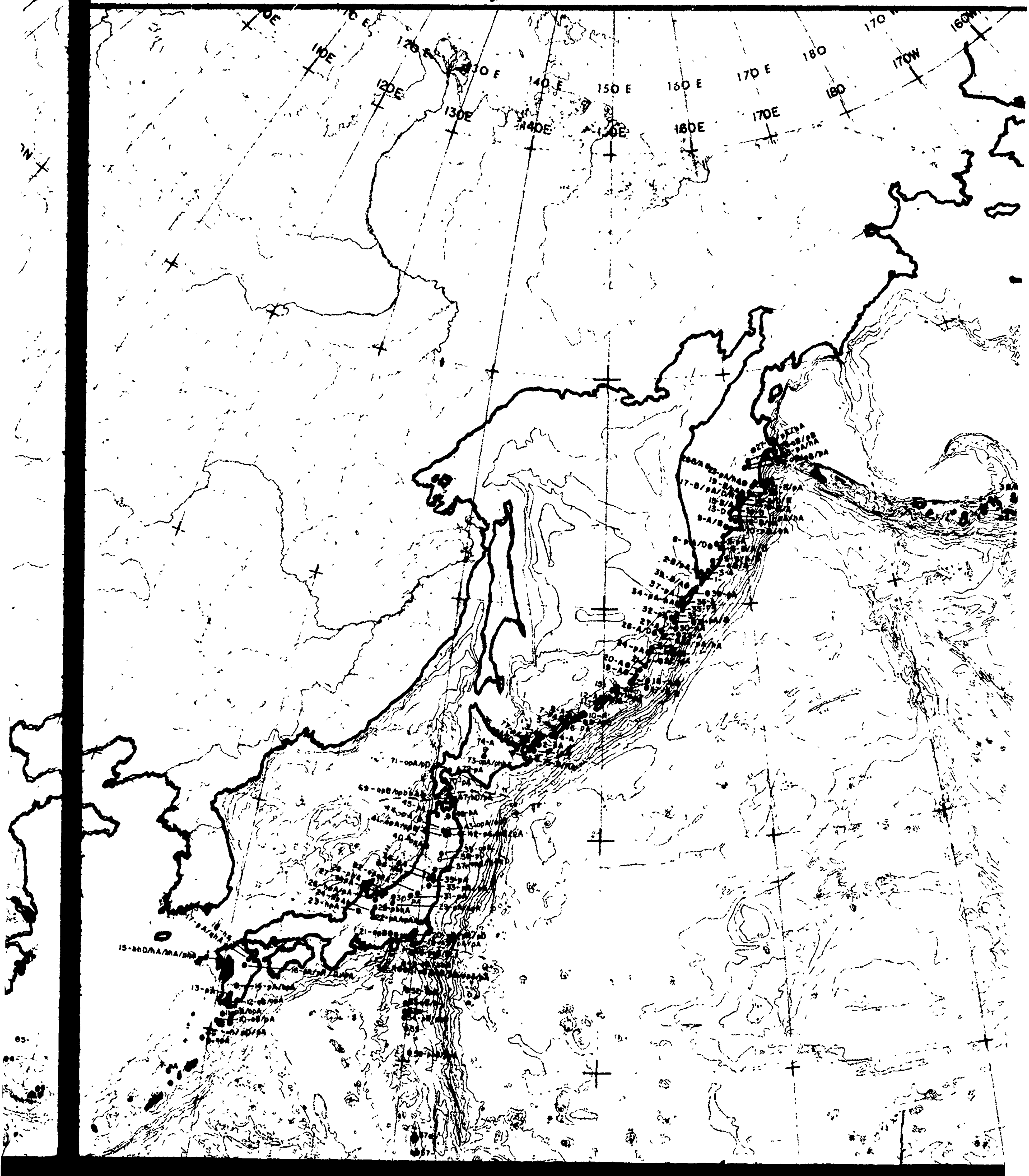
Northwestern Pacific Region

TECTONIC FEATURES

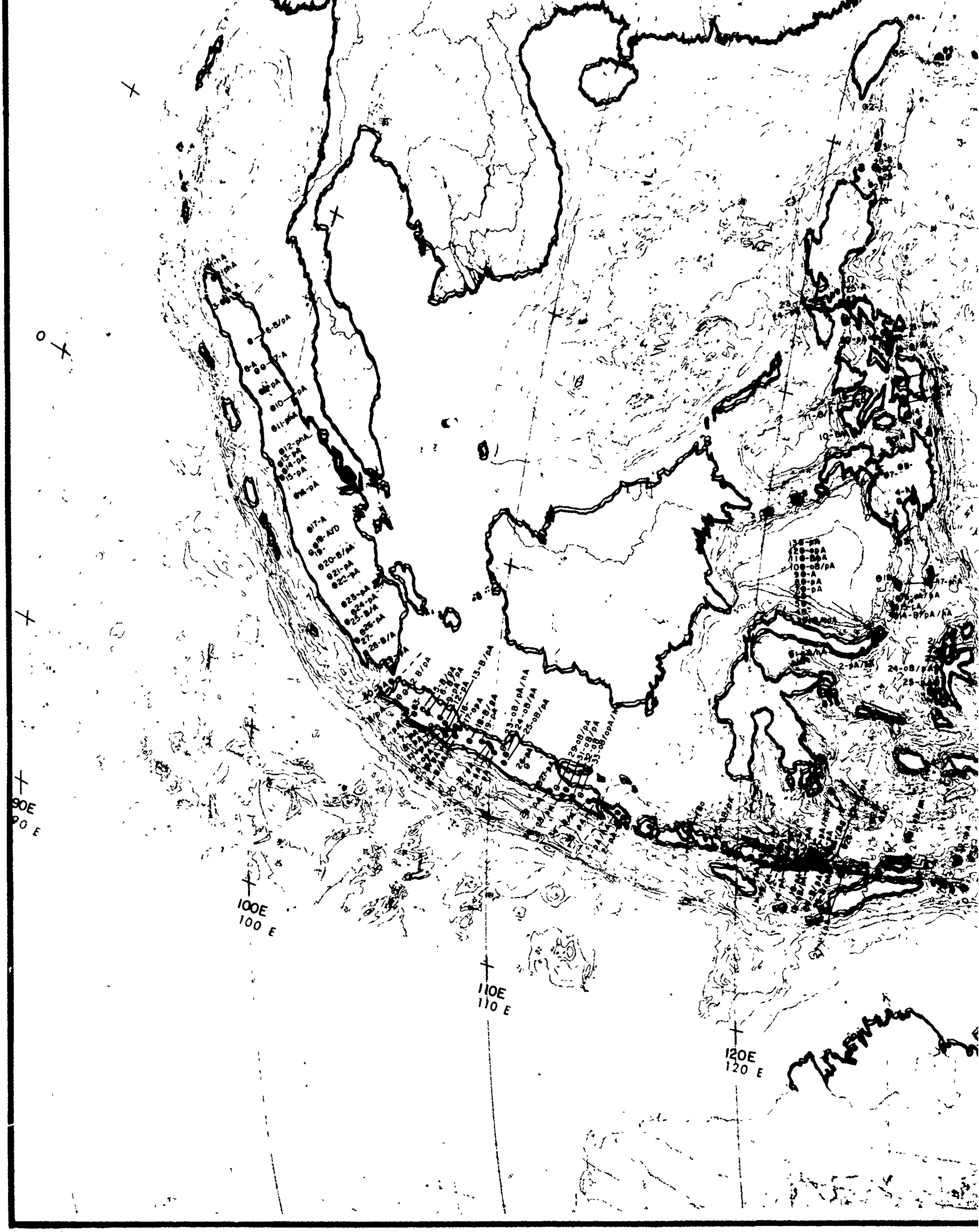
Plate XIV


40N
30N
40N
60N
30N
20N

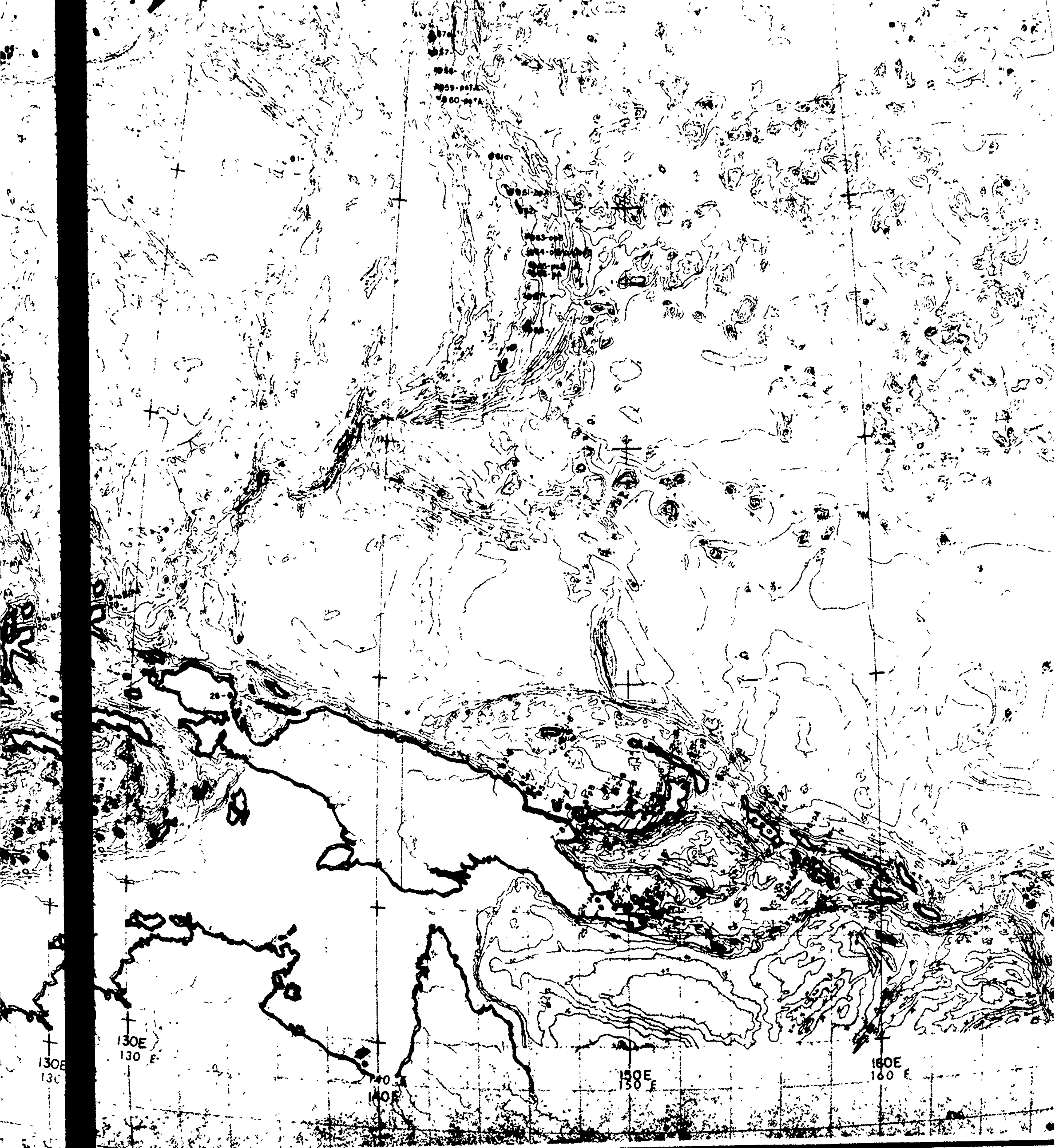
2

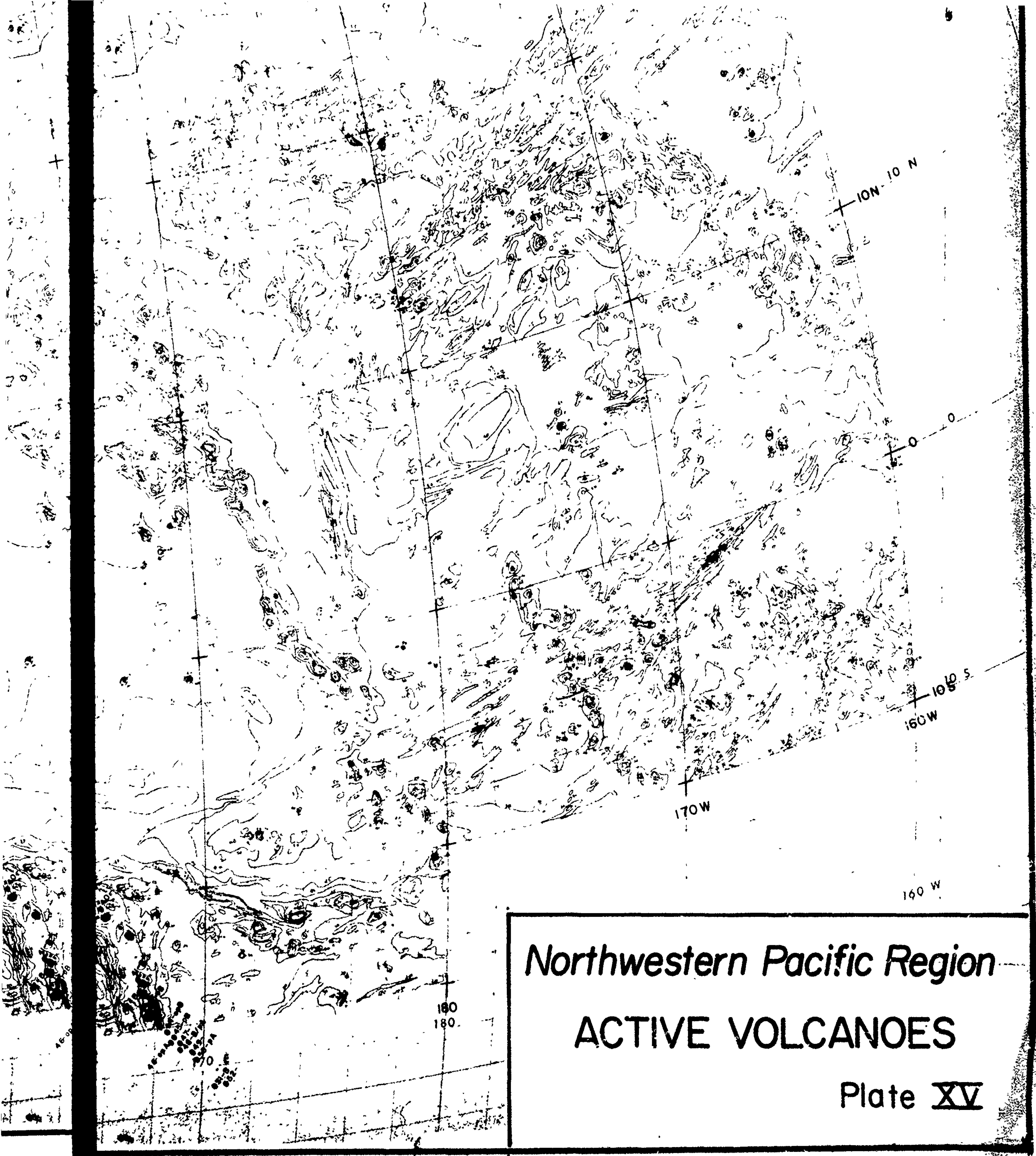

110E
120E
130E
140E
150E
160E
170E
180
170W
160W
130 E
140 E
150 E
160 E
170 E


160W
60N
50N
50 N
40N
40 N
30N
30 N
20N
20 N



4

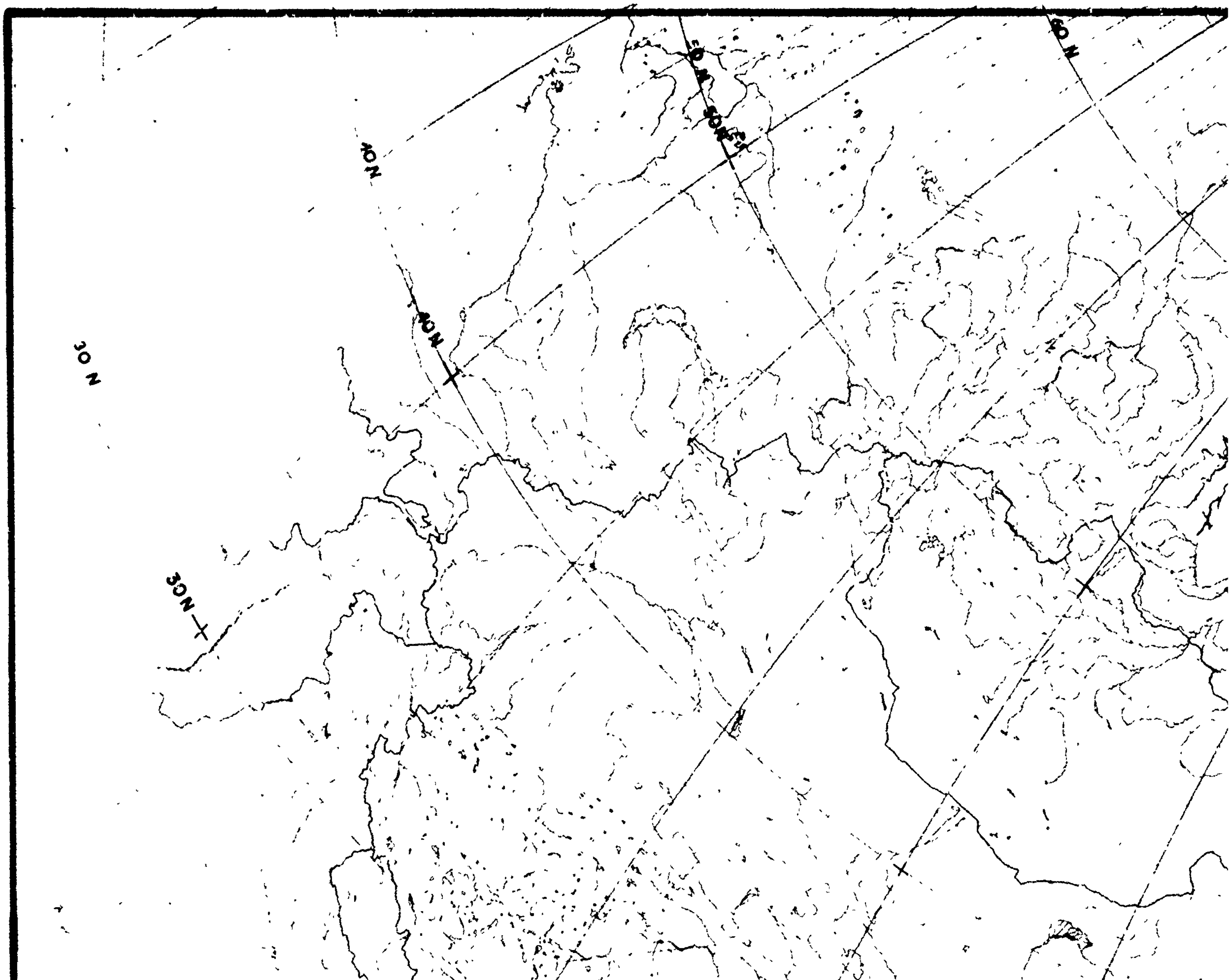

130E
130 E
140E
150E
150 E
160E
160 E



Northwestern Pacific Region

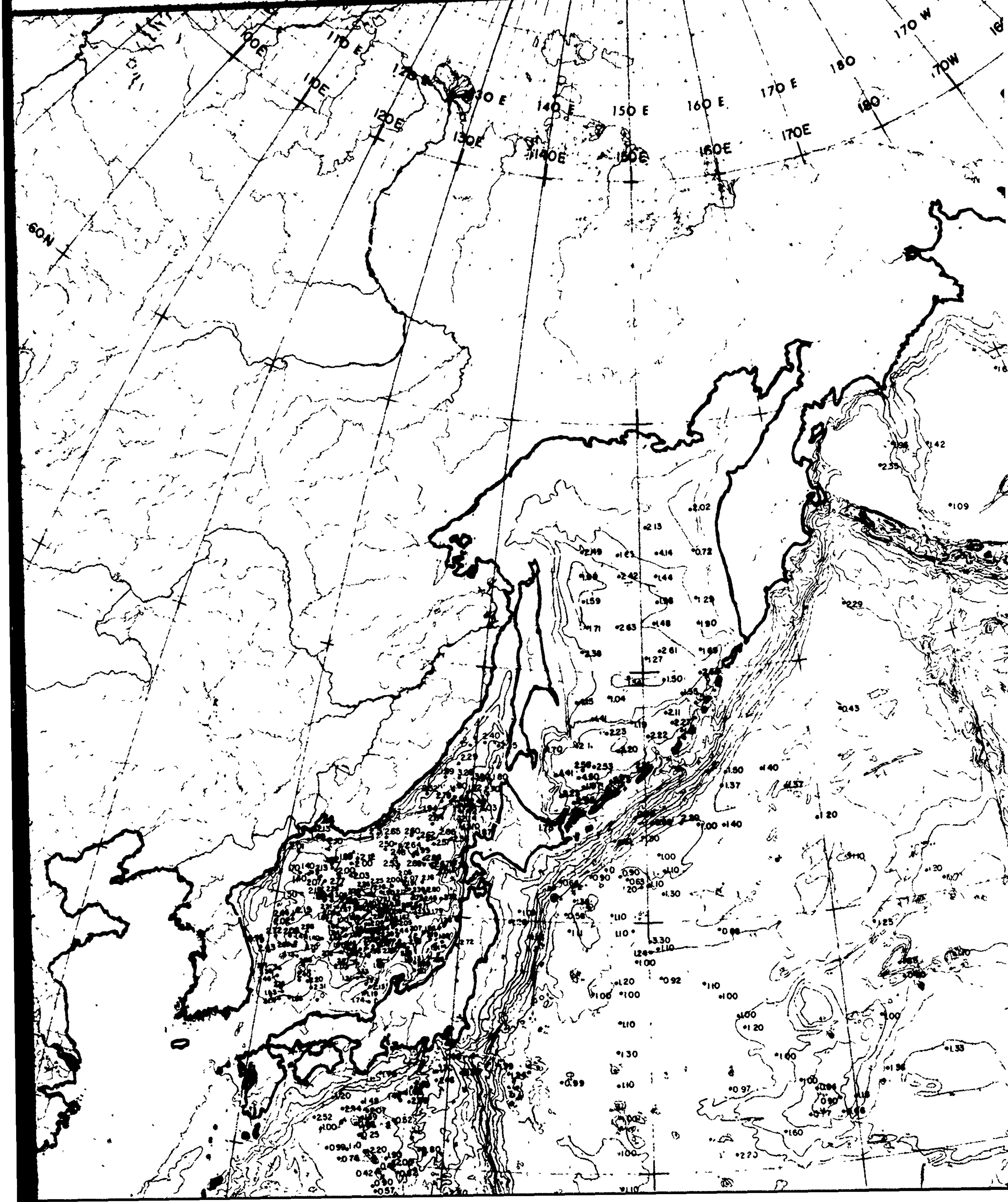
ACTIVE VOLCANOES

Plate XV



40N
60 N
30 N
30N
20 N
20N
10 N

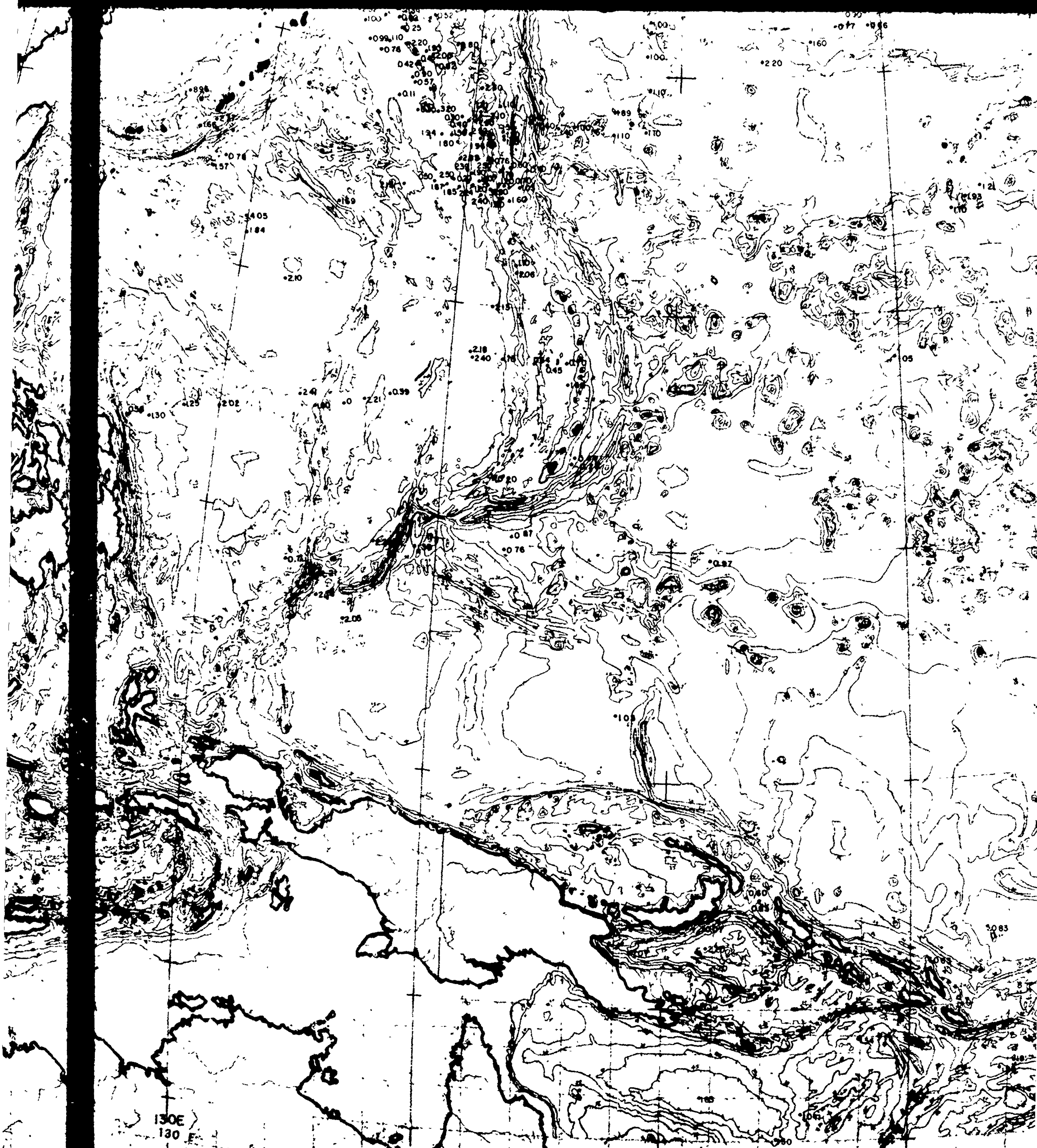
2

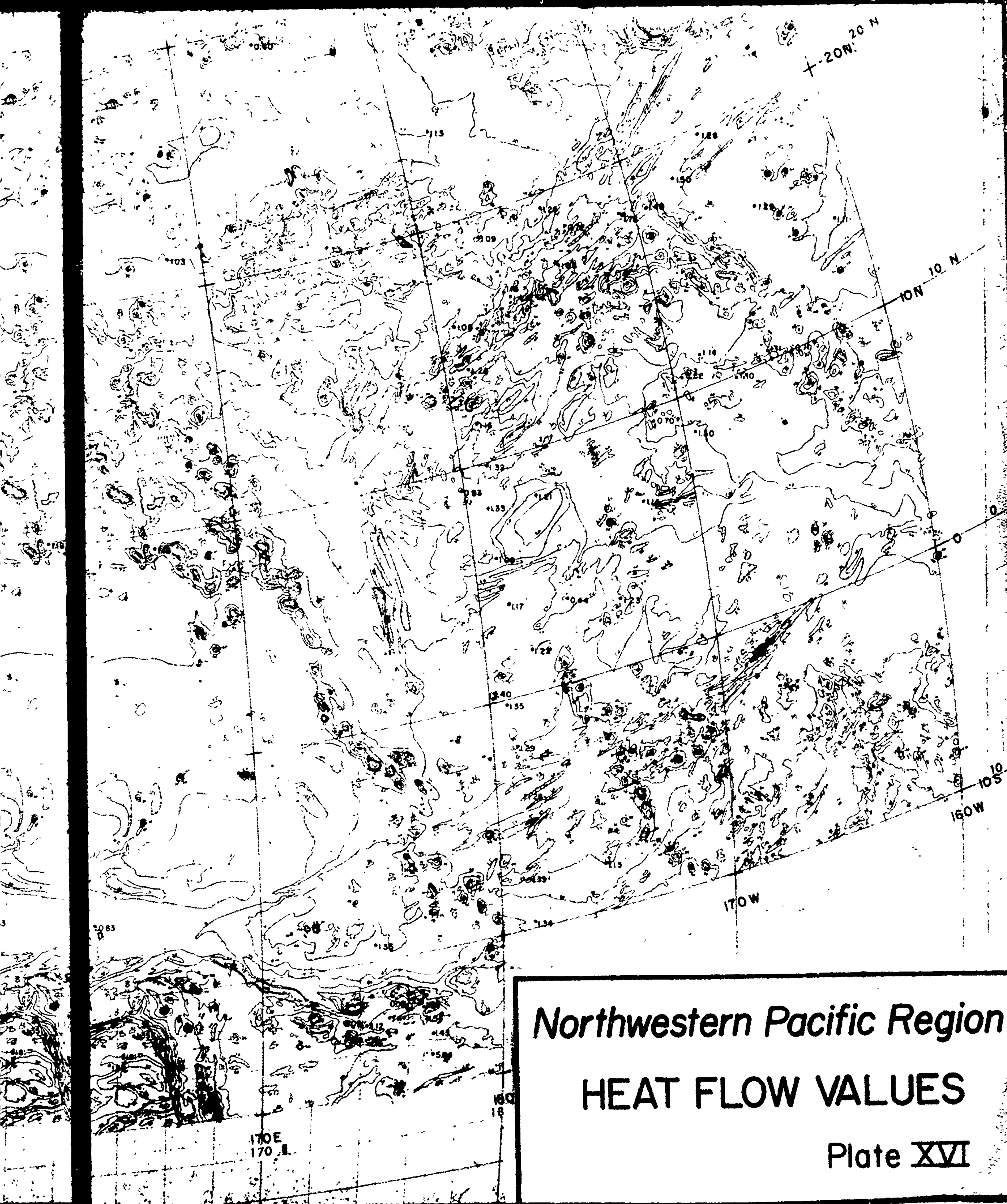


160W
170W
160W
60N
50 N
50N
40 N
40N
30 N
30N
20 N
20N


10 N
0
0
0 S 10S
90E
90 E
100E
100 E
110E
110 E
120E
120 E
230
230
148
150

4

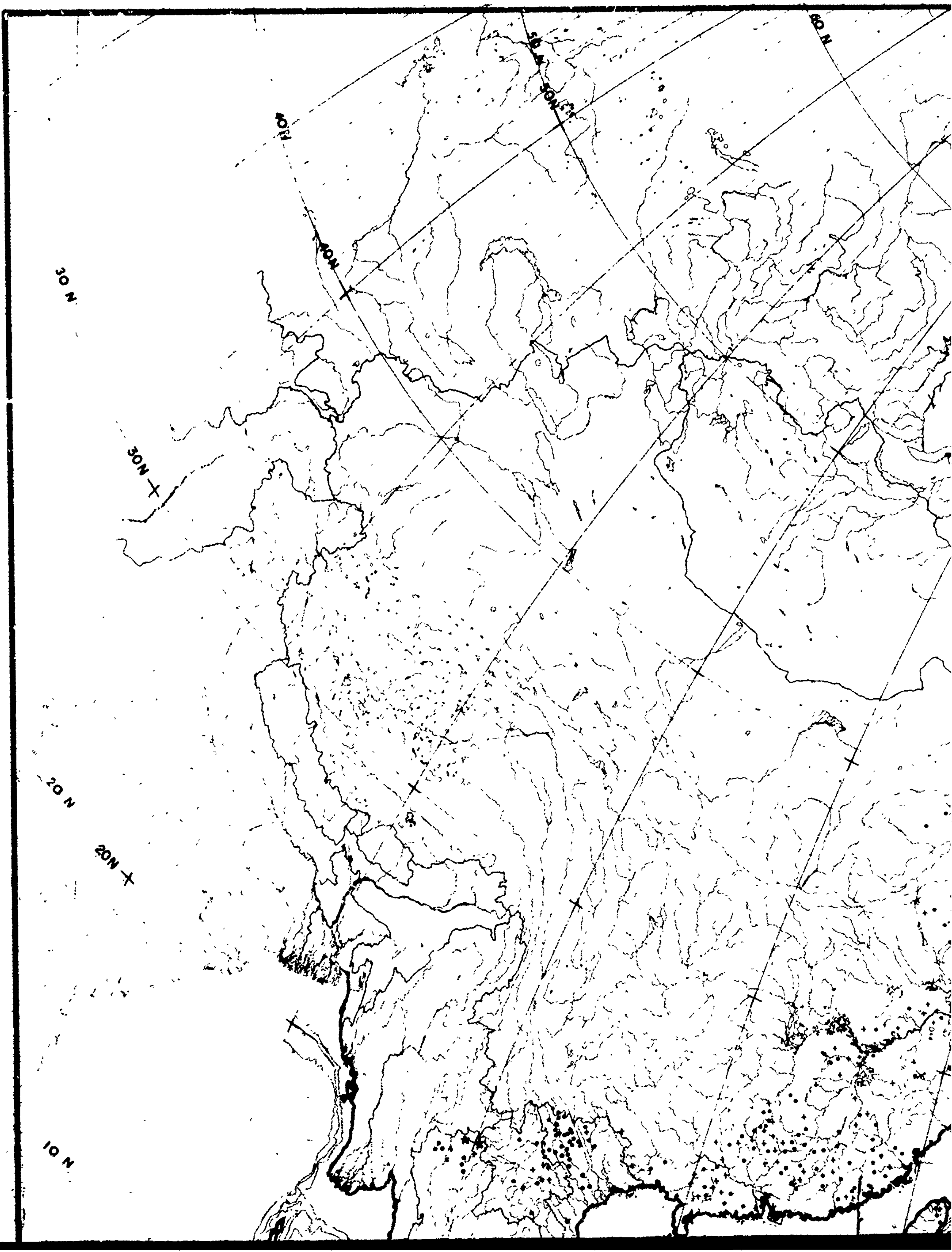

130E
130 E
140E
150E
150 E
160E
160 E



Northwestern Pacific Region

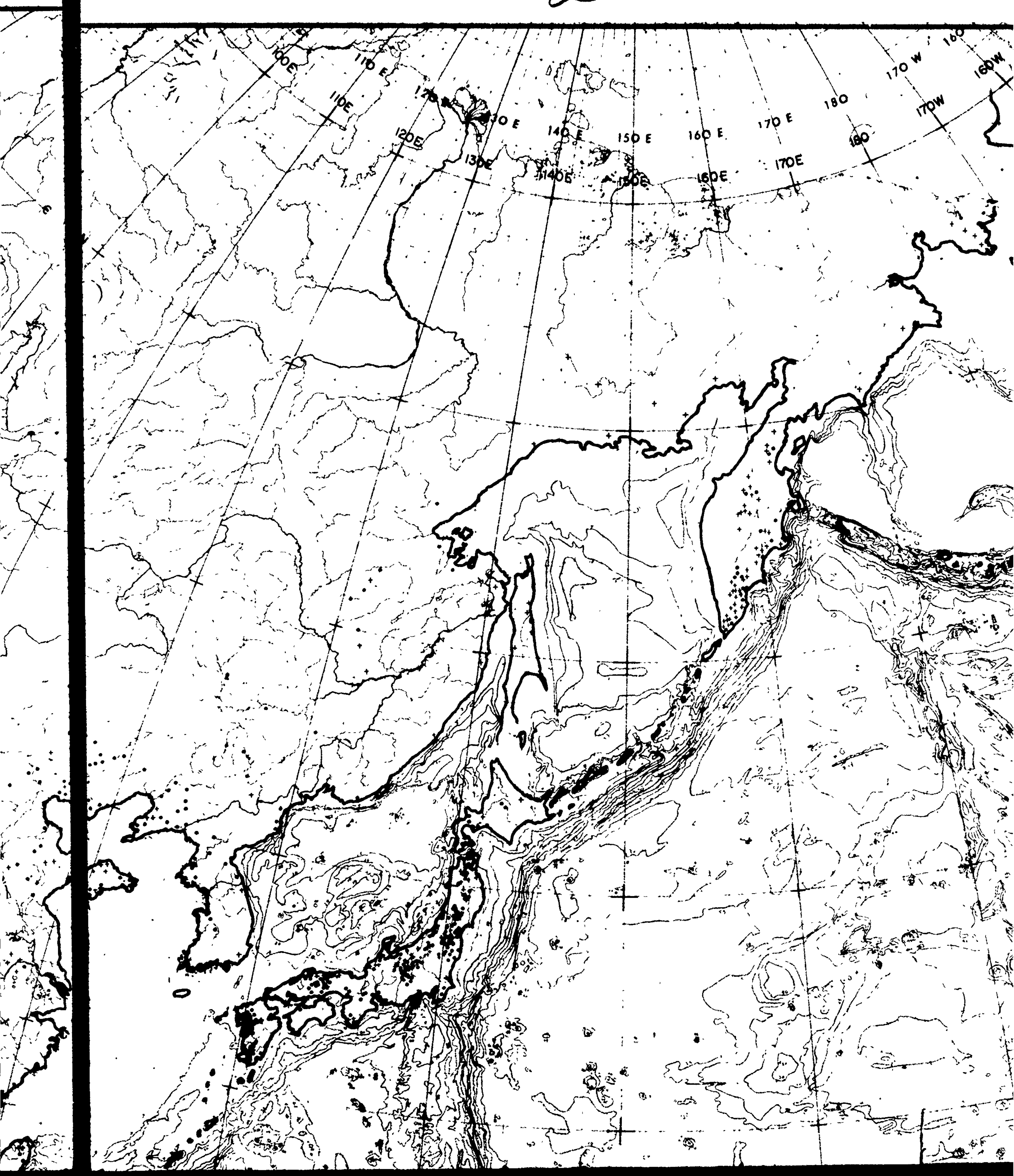
HEAT FLOW VALUES

Plate XVI

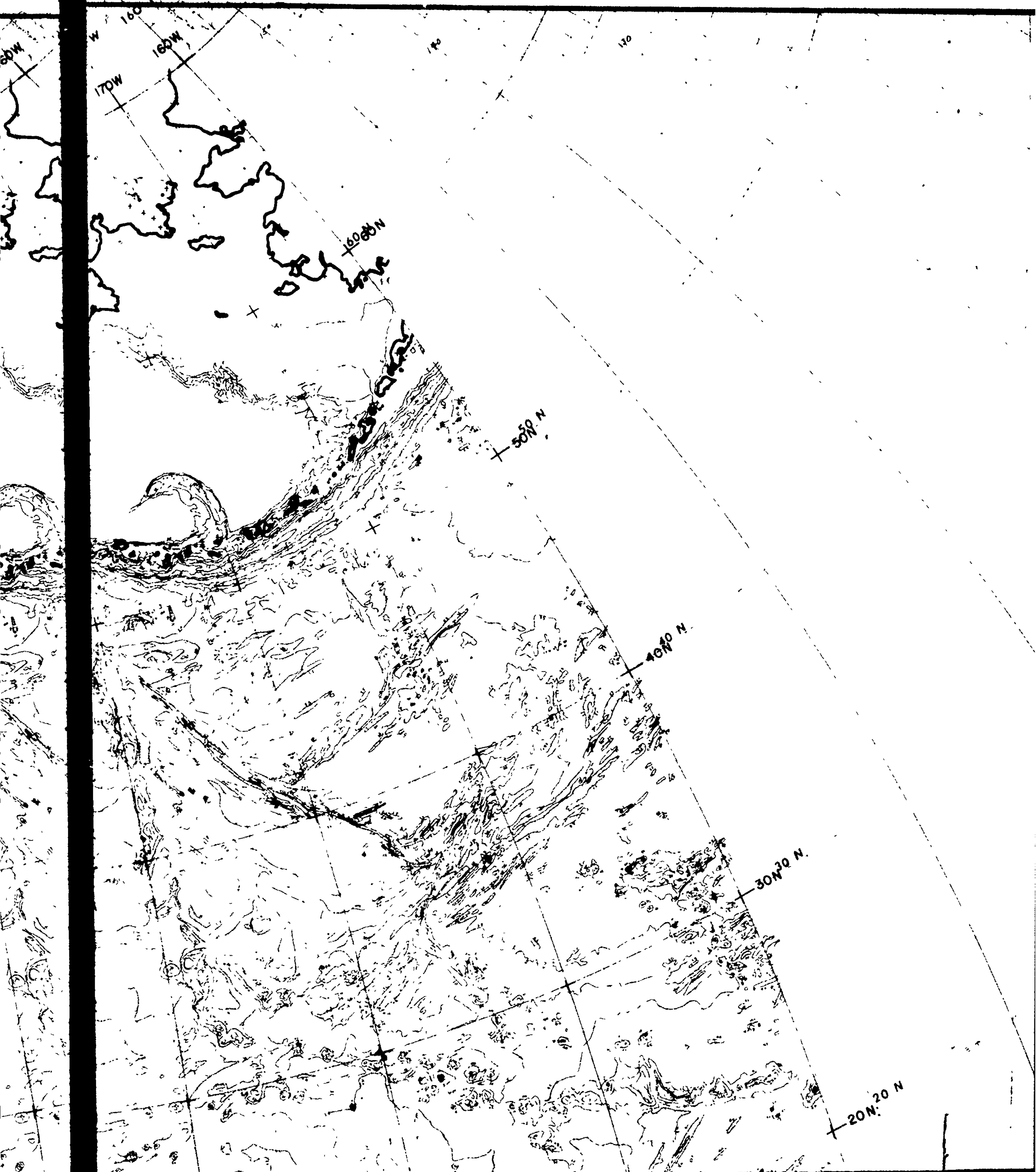


60 N
50N
40N
30 N
30N
20 N
20N
10 N

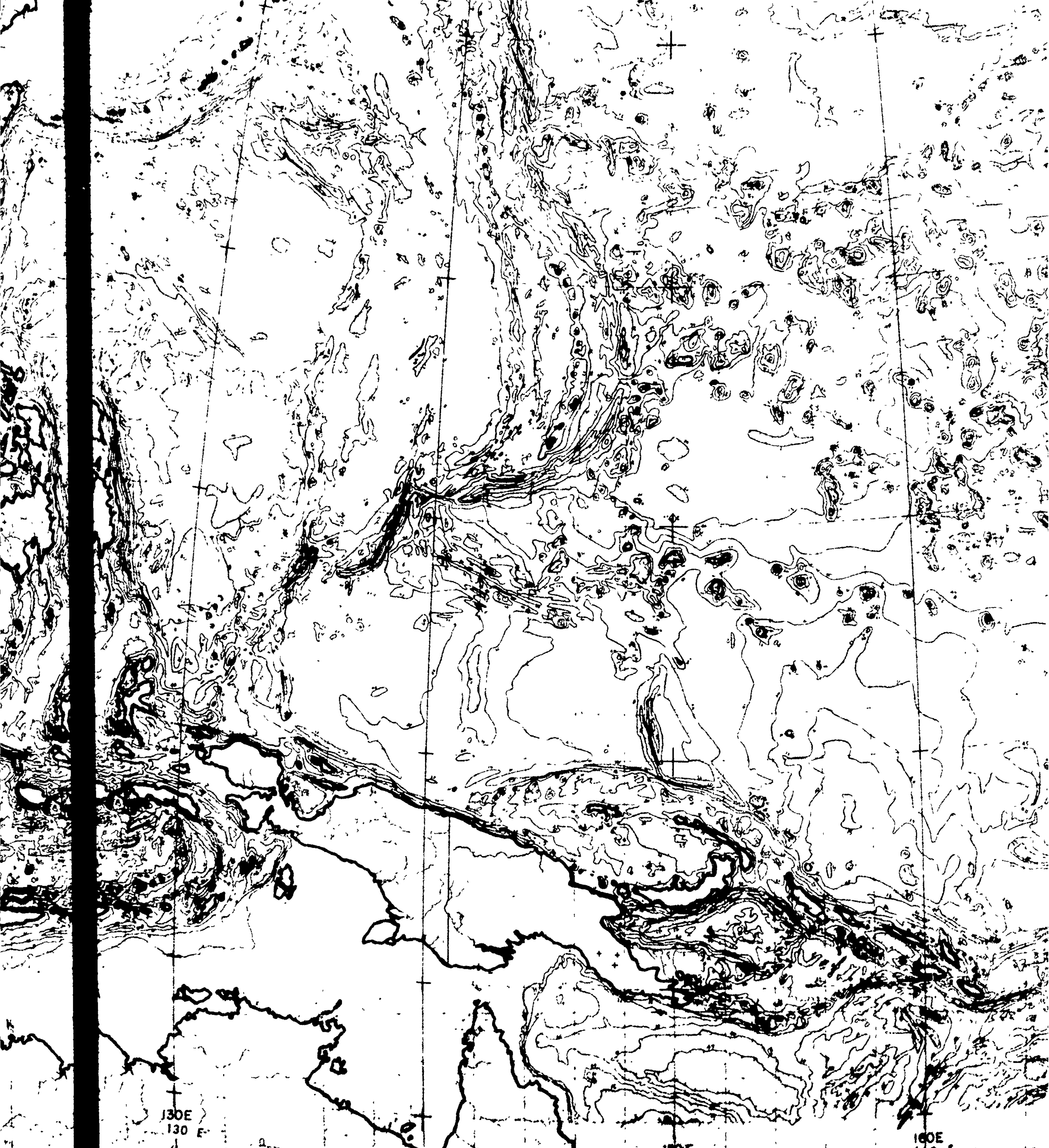
2



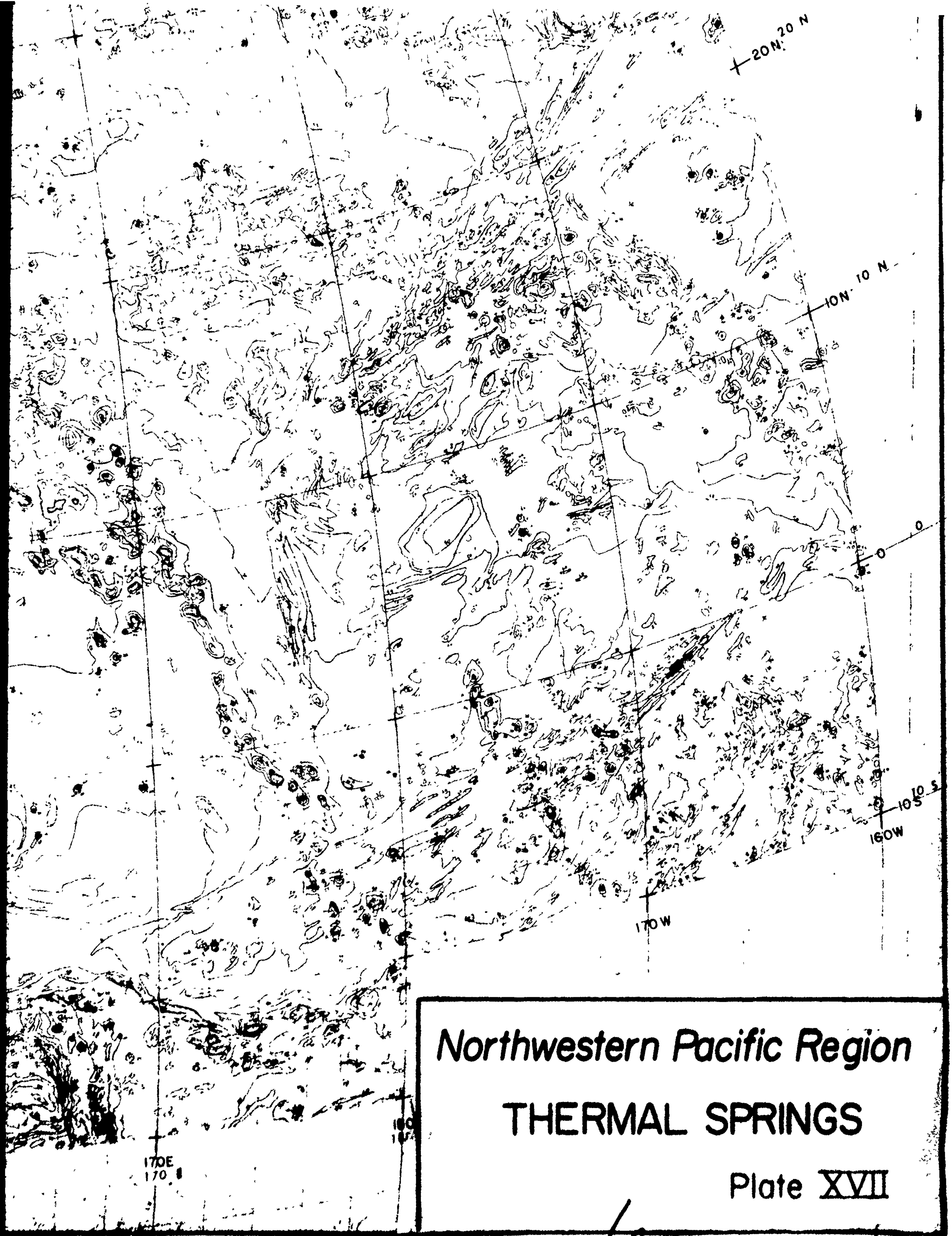
100E
110 E
110E
120E
130 E
130E
140 E
140E
150 E
150E
160 E
160E
170 E
170E
180
180
170 W
170W
160W


160W
170W
160W
60N
50N
40N
30N
20N
50 N
40 N
30 N
20 N

4



5



Northwestern Pacific Region

THERMAL SPRINGS

Plate XVII

6